Wednesday 10:35-11:35
Session 2A
General Overviews

PROMOTING TES SYSTEMS IN SWEDEN

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Swedish nuclear plants are slowly being shut down as a result of a referendum in 1980. This was one starting point for the thermal energy storage (TES) expansion in Sweden. Now, the new EU directive on energy efficient buildings forces HVAC engineers and civil engineers to look for new methods to reduce electricity consumption and to improve energy performance in new and existing buildings. This offers another platform for the promotion of TES technology in Europe. Ground source heat pumps for single family houses have become increasingly popular in Sweden during the last decades and are now one of the most common heating systems in Sweden, covering about 15% of the total space heating demand. Several hundred larger TES systems were taken into operation during the last decade. However, TES technology is still "unconventional" since most HVAC engineers and estate owners lack knowledge and experience of TES. More education is needed. This should be done through courses and workshops, books, media contacts, and efficient lobbying preferably in cooperation with the HVAC sector. The non-profit organization Swedish Society of HVAC Engineers (SWEDVAC) has since 2002 been active in bridging the gap between TES experts, HVAC engineers, and practitioners. This paper summarizes the TES expansion in Sweden and suggests some explanations for its rapid growth. It also demonstrates recent efforts to make HVAC engineers, practitioners, and property owners advocate and suggest TES systems as a standard option for space heating and cooling. The long-term aim is to make TES a conventional technique in implementing the EU directive.

R&D PROGRAMME ON THERMAL ENERGY STORAGE IN GERMANY

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The paper presents an overview of the scope and topics of R&D on thermal energy storage in the Energy Research Programme of the Federal Government in Germany. The energy policy is devoted to the protection of the climate by preventing a further increase of energy related CO_2 emissions into the atmosphere. High priority is given to the utilization of new renewable energies and energy efficiency technologies. A major subject is R&D on thermal energy storage which is a key component in many energy efficient systems. Major R&D topics in the Programme on thermal energy storage are: (1) Long Term Thermal Energy Storage (2) Phase Change Materials (3) Thermo-Chemical Storage.

The Programme is focused on applied research and development of new innovative storage technologies and concepts. The Programme comprises all promising innovative energy storage technologies. A major subject is demonstration of the technical and economic feasibility in pilot and demonstration plants by long term monitoring and data evaluation. Some projects are highlighted.

Wednesday 11:15-12:35
Session 3A
General and UTES Overviews

STATUS OF UNDERGROUND THERMAL ENERGY STORAGE IN BELGIUM

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Nowadays the acceptance of using underground thermal energy storage for applications where heating and cooling is required, is slowly forcing a way in Belgium without being a "booming" market. Two UTES concepts are now commercially available on the Belgian market: the ATES (aquifer storage) and the BTES (borehole storage). Today, more then ten, all large, ATES systems (> 500 $kW_{cooling}$), most of them located in the Campine, are installed, in operation and monitored over a period of 3 years. Due to the hydrogeological limitations, the most interesting regions and cities of Belgium are not suitable for ATES technology. Operational failures such as mal functioning control systems are quite common in the earlier projects still indicating that ATES applications requires an on-going learning process. On the other hand the large energy efficiency and energy savings from ATES projects are in favour of expanding the market growth. It became necessary to find alternative solutions for these regions, this is provided by borehole thermal energy storage (BTES).

The interest in BTES applications is slightly growing in Belgium with several feasibility studies and some concrete projects in 2006. The applications are mainly related to combined cooling and heating of office buildings and hospitals with a maximum heat pump power of 500 $kW_{cooling}$. Recently the interest in thermal response test and GSHPs is also growing. However the knowledge on the designing and thermal characteristics of the underground becomes available by a number of limited companies. In situ thermal response test are recently becoming a standard measurement for BTES projects.

Furthermore the interest of several market actors (drilling companies, engineering, consulting companies, etc) towards UTES is increasing slowly. Development work has been performed on the design of a thermal response test trailer at VITO for measuring thermal characteristics of the underground. Also some research projects have been performed on the effect of different filling material in combination with single, double U-tubes and coaxial tubes.

Wednesday 11:15-12:35
Session 3B
PCM/TCM/Solar Overviews

APPLICATION OF ICE-STORAGE IN CHINA

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The preferential electrovalence policy in many Chinese regions promotes the popularization of ice-storage technology. This paper introduces the development of ice-storage projects in the past decade, the number of projects and cool-storage capacity with different ice-storage products. Also, main characteristics of the built projects are analyzed. It is indicated that application of ice-storage projects is becoming prevalent and the technology and products are increasingly grown up. However, the number of practical projects is still small when compared with the potential of electricity peak load shaving and there is a widely developing space for the future.

Wednesday 12:35 – 2:25 and 6:00-8:00
Session 4A
Topics in Underground Thermal Energy Storage

AQUIFER THERMAL ENERGY STORAGE – PROJECTS IMPLEMENTED IN GERMANY

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Seasonal thermal energy storage is an important and often decisive component of the development of promising and innovative energy supply concepts. An interesting technique is the storage of thermal energy in aquifers. The seasonal storage of thermal energy in aquifers allows for the shifting of solar energy, surplus industrial waste heat and heat arising from cogeneration plants for the heating of buildings from summer for use in winter.

Another interesting application of aquifer thermal energy storage is the storage of ambient cold in winter for air conditioning in summer. A complete storage cycle (injection, storage and recovery) was successfully tested in a shallow aquifer at Dresden (SE Germany) in 1983 already.

The application on an industrial scale started in the 1990s after extensive preliminary investigations.
In the following, the first field test and three working systems are presented and in addition, the operational experience gathered so far is described, respectively

AQUIFER THERMAL ENERGY STORAGE APPLICATION IN GREENHOUSE CLIMATIZATION

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The aim of this study is to determine the heating and cooling potential of the greenhouses in the Mediterranean climatic zone, with aquifer thermal energy storage (ATES) known as one of the underground thermal energy storage application systems (UTES). In recent years greenhouse production reached to 44.000 ha in Turkey (Daşgan 2003). For high yield and quality in greenhouse crops during the winter months, inside temperature should be maintained at the critical value that can change depending on the species grown in greenhouse. For instance, for tomatoes the critical inside temperature should be maintained not below 12-13 ^{0}C in the greenhouse. Due to this information and also last 20 year's climate data in Mediterranean Region a greenhouse needs approximately 150 kW heating load during 90 days in a year, 8 hours in a day (Baytorun ve Abak 1995). To provide this heating load, 6L/m^2 No 6 Fuel-Oil or 9kg/m^2 coal must be consumed. The fossil fuel consumption leads to an economic burden in the operating cost, besides ashes and undesirable gas emissions from coal combustion are the biggest barriers of the greenhouses in the Mediterranean zone. Additionally, the cooling requirement of the greenhouses for early autumn and spring months in the Mediterranean Climate and the advantages provided after cooling applications will be calculated.

For these purposes, two separate greenhouses, each having an area of 360 m^2, in the research station of the Horticulture Department - Faculty of Agriculture have been selected.. One of them will be heated and cooled by ATES technique (Figure 1). In the second one conventional heating system will be used and there is no cooling system. Tomato and eggplant vegetables will be grown in the greenhouses.

Consequently, these two different systems/greenhouses will be compared in terms of economical, environmental and agricultural aspects.

ENHANCED HEAT TRANSFER FOR VERTICAL BOREHOLE GROUND HEAT EXCHANGERS

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The development of the ground source heat pump (GSHP) has made it to be feasible to utilize the thermal energy of the earth. The advantages of using the GSHP systems for heating or cooling a building are very obvious. The thermal energy from the earth is renewable and sustainable. The application of such energy has no pollution to the environment. The GSHP system can save about 30 ~ 50% more energy than air-source heat pumps. However, the shortcoming of the GSHP is that the heat conductivity of the ground soil is so low that the system has often to occupy a big area of land and requires a large scale of ground heat exchangers. Therefore, to effectively apply the GSHP, engineers and researchers are forced to study the enhancement of heat transfer to improve the effectiveness of ground source heat exchanger. In this paper the authors introduce their recent research typically for exploring heat transfer enhancement of the ground heat exchangers. Experimental study was carried out in the test filed on the ground heat exchangers of a closed-loop GSHP. A new type of screwed core tube bundle was used in both coaxial vertical boreholes, 100m depth and 150mm diameter; 200m depth and 100mm diameter, respectively. Impressively, the experimental data shows that the heat capacity of extracting energy from borehole is about 75~100W/m and the heat capacity of rejecting energy to the ground is about 240~280W/m. Indeed, it is indicated that this type of canular flow can increase the efficiency of heat transfer and make better use of the earth thermal energy.

MODELING OF VERTICAL GROUND LOOP HEAT EXCHANGERS WITH VARIABLE CONVECTIVE RESISTANCE AND THERMAL MASS OF THE FLUID

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The ability to predict the short-term behavior of ground loop heat exchangers (GLHE) is critical to the design and energy analysis of ground source heat pump (GSHP) systems. For short-term behavior of GLHE, the thermal mass of the fluid is important, especially when dealing with strong short time-step fluctuations due to rapidly changing building loads. For peak loads of short duration, say one to two hours, the thermal mass of the fluid can significantly dampen the temperature response of the ground loop. The over prediction of the temperature rise (or fall) in turn can cause an over prediction of the required GLHE length. Furthermore, the temperature response can be damped by the fluid in the rest of the system, in addition to the fluid in the borehole. In GSHP systems, antifreeze mixtures are often used as a heat transfer fluid. The flow rate in the GLHE is generally set so as to ensure turbulent flow to guarantee a low convective heat transfer resistance. But, particularly for some antifreeze types, the large increase in viscosity as the temperature decreases may result in laminar flow, or require an otherwise unnecessarily high system flow rate. It is therefore desirable to be able to properly account for the thermal mass of the fluid in the entire system, and investigate time-varying flow rates and convective resistance due to changing fluid properties.

This paper presents a new short time-step model for vertical GLHE. Like the Yavuzturk and Spitler (1999) model, it is an extension to the long time-step Eskilson model (1987). The model described in the paper replaces the response function approach at short time-steps with a one-dimensional numerical model, which explicitly accounts for the thermal mass of the fluid and the convective resistance as a function of flow rate, fluid mixture, and fluid temperature. The paper also describes an approach for representing the two-dimensional borehole geometry in one dimension, utilizing the multipole method for calculating the

thermal resistance of the grout, while maintaining the correct thermal mass of the grout. Validation and implementation of the model, along with an example application are also described.

THERMAL RESPONSE TEST WHILE DRILLING

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Thermal Response Test (TRT) has become a standard method performed to evaluate borehole and bedrock thermal properties before designing larger borehole heat exchanger (BHE) systems. Such measurements are usually made in one borehole in which heat is injected at constant power. A mean value of the thermal properties of the BHE is determined by analysing the temperature change in the borehole. In Thermal Response Test While Drilling (TRTWD) heat released during drilling causes a temperature change in the borehole which is used to perform a similar evaluation. Current work on this method is based on the water-driven down-the-hole hammer. In this drilling method supplied drilling energy dissipates into heat in the hammer tool at the bottom of the hole. The effective thermal conductivity of the bedrock is evaluated from measured inlet and outlet temperatures, fluid flow rate and energy injection. In TRTWD measurements the bedrock thermal conductivity is continuously evaluated as a mean value for actual borehole depth. As the borehole is getting deeper changes in bedrock properties will be embedded in measured data. Providing that temperature measurements are made with high resolution and accuracy the effective thermal conductivity would be continuously determined along the hole. This means that bedrock anomalies, such as fissures and lithological boundaries, could be detected with this new method. This increased information on all drilled boreholes is useful for system design but could also be used for geological (geophysical) mapping. A numerical model estimating the heat transfer during drilling has been made and used to analyse the potential of such measurements. Provided that detailed temperature measurements can be made, bedrock conductivity may be evaluated and occurring anomalies are detectable.

IMPACT OF THERMAL BUILDUP ON GROUNDWATER CHEMISTRY AND AQUIFER MICROBES

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The academic buildings of the Richard Stockton College of New Jersey are heated and cooled by a large-scale, closed-loop, ground-coupled, heat pump system. Heat is exchanged in a borehole well-field that is traversed by three aquifers. The system has been in operation since 1994 and a thermal buildup has occurred since more heat is rejected by the system than extracted. The well field was designed with monitoring wells which allow access to the underground environment, and studies have been conducted to determine how groundwater quality and aquifer microbiota have been affected by the temperature increase. The temperature increase is as much as ten degrees Celsius within the well field and the thermal effects have spread downstream. The temperature fluctuations are in a range that is critical for the optimum growth of several broad groups of bacteria. While no significant differences were observed for groundwater pH, conductivity, preliminary work indicates changes to the aquifer microbial community. Recent addition of a cooling tower to the system is expected to correct the thermal imbalance and bring the temperature back to ambient conditions. The specific changes in the aquifer microbiota suggested by our work provide a basis to evaluate whether the aquifer microbial community will recover once the thermal imbalance of the well-field is corrected. This work highlights the need to consider the overall thermal balance in system design to maximize efficiency and minimize the environmental impacts.

THE CONTINUED WARMING OF THE STOCKTON GEOTHERMAL WELL FIELD

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Temperatures within the Stockton College Geothermal well field have risen by as much as 11^{o}C since it commenced operation in 1994. More heat is stored within the field during the air conditioning season than is removed during the heating season. Temperature increases have varied depending on whether the layers affected are aquifers or confining bed. Groundwater flow in the Upper and Lower Cohansey aquifers has functioned like a "stiff breeze", drawing cooler groundwater into the well field while advecting heat accumulated during its operation downflow. The deepest aquifer, the Rio Grande water-bearing zone, does not share this characteristic and seems merely to be accumulating heat.

Wednesday 12:35-2:25
Session 4B
Topics in PCM/TCS/Solar

RESEARCH ON THERMAL STORAGE USING ROCK WOOL PCM CEILING BOARD

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This study examined the effects of a peak shaving control of air conditioning systems using PCM (Phase Change Material) for ceiling boards in an office building. Rock wool PCM ceiling board (PCM ceiling board) was enhanced by adding microcapsulate PCM, with a melting point, of about 25 ˚C, close to room temperature. The load on the air-handling unit (AHU) can be reduced by using the thermal storage of the PCM ceiling board during the peak shaving control period. During overnight thermal storage, cool air from the AHU flows into the ceiling chamber space and chills the PCM ceiling board, storing cooling thermal energy. During the peak shaving period, when the thermal load peaks, the air from the room returns to the AHU via the ceiling chamber space. As a result of passing through the cooled-down PCM ceiling board, the warm air returning from the room cools down before returning to the AHU. The maximum thermal load and the capacity of heat source can thus be reduced.

The thermal capacity of the PCM ceiling board was measured by using a small experimental chamber. The thermal capacity of the PCM ceiling board is approximately 663 kJ/m^2, which is 4.9 times that of an ordinary rock wool ceiling board. The effects of peak shaving control were examined, using PCM ceiling board in the experimental chamber. The maximum thermal load using the PCM ceiling board was 85.2% of that of using rock wool ceiling board. It can reduce the load on the AHU. However, the integrated thermal load was 5.3% greater than that using the rock wool ceiling board. The transition rate of the thermal load to the night was 25.1%. Discounted nighttime electricity, which is 75% cheaper than daytime electricity, can be used in Japan. The running cost is 91.6% lower than that of using the rock wool ceiling board. From these results, it can be concluded that the PCM ceiling system acts effectively to enable peak shaving control.

A STUDY ON A PRACTICAL MEASUREMENT OF THERMAL CHARACTERISTICS PHASE CHANGE MATERIALS FOR BUILDING USE

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Thermal energy storage (TES) is promising measure for energy conservation and environmental issues. Some researchers have focused on Phase Change Materials (PCMs). PCMs can store heat in constant phase change temperature and release it in different time. The effect of PCMs are temperature stabilization in room, peak load shifting to off peak and utilization of natural energy sources.
The information on thermal properties of PCM is inevitable to use PCM effectively. A differential scanning calorimeter (DSC) is a poplar devise to decide melting temperature and heat of fusion. It, however, uses only tiny sample of PCM and the results are depended on temperature gradient during testing. Measurements using larger samples, such as T-history method, are proposed by several researchers.
The authors conducted experiments for measuring PCM's properties with realistic amount of samples and proposed two simple methods to predict the values. One method used heat flow transducers. The small amount, 50 mL, of PCM was packed in a flat container of which two surfaces were covered by heat flow transducers and heated and cooled in the pre-decided conditions. Heat flows and temperatures during heating and cooling were measured and a relation between enthalpy changes and temperature was derived.
Another method proposed in this study did not need special devises such as heat flow transducers. It was modified T-history method, which measures temperature under temperature fluctuation. Comparing temperature fluctuation between PCM and the reference, thermal characteristics could be derived. The experiments were also conducted in various temperature gradients of heating and cooling. The accuracy of this method was discussed by comparing different measuring methods.
In applications for PCM in building, exact values of melting temperature and heat of fusion were not necessary, because the materials were exposed in a certain range of ambient temperature difference. The amount of heat during temperature change was important.

MIXING MODEL FOR THERMAL ENERGY STORAGE WATER TANK OF MULTI-CONNECTED MIXING TYPE

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Water thermal storage tank of multi-connected mixing type is the most popular water thermal storage tank in Japan. The water storage tank uses effectively spaces between footing beams of building base, therefore the construction cost of tank is relatively low. The thermal energy storage tank is generally consisting of more than 15 tanks connected in series with connecting holes. The connecting holes arrangement is decided to prevent a short-circuit stream through the tank. The performance of thermal storage tank is reduced by the short-circuit stream. And the input conditions have a great effect on the mixing behavior in the tank. In this paper, a mixing model which can be applied to multi-connected mixing type thermal storage tank is presented. The mixing model is based on the mixing model for temperature-stratified thermal storage tank, and is extended to applicable to multi-connected mixing type of thermal storage tank. It is assumed that vertical one-dimensional diffusive and convective heat transfer is considered and inflow water from inlet pipe or connecting hole is mixed with the tank water in a region according to input conditions and vertical temperature distribution in the tank. The depth of mixing region is calculated by the experimental equation which is a function of Archimedes number. Experiments carried out in the model tank which consists of four tanks connected in series. When the connecting holes were made at the bottom of tank partition in series, the upper part of each tank is not used effectively for thermal storage. When the connecting holes are arranged upper and lower alternately, the tank water tended to be mixed well even if velocity of inflow is relatively low. And the temperature profiles in the tank calculated by using the mixing model were compared with the results of experiments. It was found that the calculated results by using the mixing model agreed with the experimental results.

STABILIZATION OF GLAUBER'S SALT WITH SUPPORT MATERIALS AND USING AS PHASE CHANGE MATERIAL

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Thermal energy storage systems (TES) have attracted increasing interest for thermal applications such as hot water, space heating and cooling. These systems are useful to correct the mismatch between the supply and demand of energy. There are mainly two types of thermal energy storage systems, sensible and latent heat storage. Latent heat storage is particularly attractive due to its ability to provide a high energy storage density and its characteristics to store heat at a constant temperature corresponding to the phase transition temperature of the heat storage substance. Inorganic salt hydrates as latent heat storage materials have certain advantages over organic materials in the same melting temperature range. However, some problems occur when salt hydrates are used as phase change material (PCM) in the latent heat storage applications. These problems are super cooling of salt hydrates when they freeze because of their weak nucleation properties and phase separation occurring because of incongruent melting of these materials. In this study, Glauber's salt ($Na_2SO_4.10H_2O$) is stabilized with different concentrations of polyacrylamide gel and gelatin gel to prevent incongruent melting. Nucleating agent which resembles crystal structure of Glauber's salt ($Na_2SO_4.10H_2O$) was also used to prevent supercooling. Thermal storage capacities of the PCM samples which were stabilized with different concentrations of polymeric gels are determined both by Differential Scanning Calorimeter (DSC) and temperature-history methods. The results of measurements will be presented in the final paper.

EXPERIMENTAL INVESTIGATION OF THE PRESSURE-DROP OF CLATHRATE HYDRATE SLURRY (CHS) FLOW OF TETRA BUTYL AMMONIUM BROMIDE (TBAB) IN STRAIGHT PIPE

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The Clathrate Hydrate Slurry (CHS) of Tetra-n-Butyl-Ammonium Bromide (TBAB) comes into being under normal atmosphere when aqueous TBAB solution is cooled to 0 12 . It is a kind of high-density heat-transportation and cold-storage medium and it exists as slurry state (mixture of both solid phase and liquid phase). Because phase changes between liquid and solid when transporting heat, CHS of TBAB has far higher cold-loading density than that water does. On the other hand, CHS of TBAB behaves as fluid, which means it can be transported easily through pipeline. So it is very promising to apply the CHS of TBAB into air conditioning systems or central cold-supply systems for its energy-saving advantages. In this paper, the flow experiments of CHS of TBAB are carried out in straight circular pipes. And the rheology and pressure drop properties of CHS of TBAB are investigated. CHS with different volume fraction of solid phase (Φ) is produced by cooling the TBAB solution, with concentration of 22% and 30%, respectively, to different temperature. The power law property of CHS of TBAB is found in the experiments when φ is below 16%. Furthermore, the result shows the values of k and n (defined by power law) vary with φ. And the friction pressure-drop correlation is acquired by using Re_{MR} through experiments, and it is found that the correlation is suitable when Φ is below 15%.

NOVEL DESIGN OF HEAT SINK WITH PCM FOR ELECTRONICS COOLING

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The paper presents a novel design of heat sink for cooling electronics devices. It consists of thin aluminum pipes which are soldered to the thick base plate. The pipes are filled with PCM, which substantially increases heat capacity of the heat sink. Base plate and three additional walls form a structure similar to shell and tube heat

exchanger. Fan attached to one side of the spreader forces air flow across the pipes. Basic advantages of such design are: high external surface – comparable to modern heat spreaders used in electronic equipments, very high heat transfer coefficient and high thermal capacity.
First part of the paper is focused on the thermal performance of the heat sink in steady conditions, i.e. in normal mode of operation. The power, which can be removed to the environment, is estimated for different geometry configurations, e.g. for different dimensions of pipes and their packaging on the plate. Based on energy balance, pipe/fin models and correlations for heat convection in a given air flow configuration, high potential of the heat sink for cooling contemporary microprocessors was proved. Obtained values of thermal resistance of the heat sink allow predicting that such kind of heat sink can be used to dissipate heat fluxes up to 50 W. In the second part the performance of the heat sink in unsteady conditions is analyzed. The complex heat conduction problem with melting of PCM is performed using numerical techniques. Temperature variations in time in crucial points of the design are analyzed for different amount of PCM incorporated in the structure. Basically the rapid decrease of heat transfer coefficient is considered as the thermal disturbance – such situation is associated e.g. with the damage of the fan. Thermal behavior of heat sinks of different geometrical dimensions was analyzed. In all cases it was shown that even small amount of PCM (mass fraction) in the heat sink substantially improves its potential to stabilize temperature of microprocessor during abnormal operating conditions.

VENTILATION PERFORMANCE OF SOLAR CHIMNEY WITH BUILT-IN LATENT HEAT STORAGE

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A prototype of solar chimney with built-in latent heat storage system for prolongation of the ventilation system operation until evening / night or even 24 hours was designed and developed. An innovative idea has been applied to design an absorber of the present prototype solar chimney. This absorber consist a black coated aluminum (Al) plate with built-in PCMs for latent heat storage. Sodium Sulfate Decahydrate "Na_2SO_4 $10H_2O$" (melting point 32 degree C, freezing point 30 degree C, latent heat of fusion 126 kJ/kg) was used as a Phase Change Material (PCM) for latent heat storage. Experiments to evaluate the thermal behavior and airflow rate in the solar chimney with the effect of parameters such as gap spacing (100mm-300mm) between the absorbing plate and glass cover, inclination angle (45, 60 and 75 degree) under different atmospheric conditions like ambient air temperature and solar radiation etc are in progress. This paper presents the description of the prototype solar chimney with PCM storage, the method to measure the airflow rate in the chimney, the typical of measured results of temperatures and airflow rate, and a numerical simulation model to predict the airflow rate in the chimney and temperature of aluminum (Al) plate, air in the chimney and PCM.

HEAT STORAGE SYSTEMS FOR USE IN AN INDUSTRIAL BATCH PROCESS: (RESULTS OF) A CASE STUDY

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Thermal energy storage can be an attractive technology to enable re-use of waste-heat, especially for batch processes. A case study was carried out to evaluate the technical and economical feasibility of an industrial heat storage system. The study focused on integration of a heat storage system within an existing production facility of organic surfactants. Three different thermal storage systems with operating

temperatures between 110°C to 160°C were designed to store the heat released during the exothermic reaction phase and re-use the heat for preheating of the reactants in the following batch. The first system uses a Phase Change Material (PCM) contained in metal balls with an assumed phase change temperature at 140°C. The second system uses a concrete volume as a sensible heat storage material and the third system is also based on concrete, but with a doubling of the storage capacity.
A dynamic simulation was performed of a reference cycle of a batch reactor coupled with a thermal storage system to calculate energy savings for preheating of the reactants. It was required to oversize the storage capacity of the PCM system, in order to obtain a heat transfer rate that matches with the conditions of the actual process. The calculated energy savings for heating of the batch reactors is 50 to 70%, resulting in financial savings of 26 to 38 k€ on an annual basis. The total capital investment of the storage systems is estimated at 440 to 540 k€. Simple pay out time is higher than 10 years, with the best result for the concrete heat storage. The bare cost of the thermal buffer is 15% to 30% of the total capital investment. Because the cost of integration of the storage system in an existing facility are a large part of the total cost, it is recommended to evaluate the use of thermal storage systems for grass-roots situations.

Wednesday 2:25-4:05
Session 5A
UTES Overviews

EXPERIENCES WITH ATES APPLICATIONS IN FLANDERS : OPERATIONAL RESULTS AND ENERGY SAVINGS

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The first ATES system of Belgium went in operation in 1998. Until today, besides various small installations, ten large (> 500 kWt) ATES systems were installed for different applications. Several of these installations were monitored as energy demonstration projects. This concerns an initiative of the government in order to disseminate information on practical results of innovative energy technology systems. The implementation of the ATES technology went together with some unavoidable growing pains. Some of these problems were caused by the unusual combination of technologies and working parties. Drilling companies get involved in the process of HVAC installation. Most critical are the connection points between the traditional and innovative installation part, defined as the boundary zone between the underground and aboveground installation. As typical example, the communication between the control systems of the HVAC and the ATES system can be mentioned. On the principle that “To measure it… is to know it !” , an objective result overview of each project can be achieved by setting up measuring campaigns. These campaigns provide good information on the performance results and can be used to inform future interested parties in the ATES technology on the reliability, effective economical impact and benefits for the environment. It assists the persuasion of potential installation owners that the teething troubles and possible installation failures came to an end. It’s very well known that one bad working installation overrules a dozen of excellent operating systems. By comparing operational results with initial design values and by evaluation of installation specifications, lessons can be learnt for the future by designers, performers and researchers. This paper provides an overview of the operational experiences and results on three ATES systems that run for at least two years and where a extensive data logging system is available. Typically, information on energy transfer and consumption, flow rates, and temperatures is obtained. This information is compared with a predefined “reference” installation, existing of contemporary energy systems. This allows to define the actual energy savings and environmental benefits.

THE APPLICATION OF AQUIFER THERMAL ENERGY STORAGE TO A CITY CENTRE CARBON EMISSIONS REDUCTION PROGRAMME AT THE SOUTH KENSINGTON CULTURAL AND ACADEMIC ESTATE, LONDON, ENGLAND

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The majority of building stock in London and most other cities around the world pre-dates energy efficient building design. Many buildings in London are over 100 years old and even buildings that are relatively recent were designed and built in an era when energy was considered plentiful and cheap. Huge reductions in energy demand are required in the relatively short term, yet the time scale for replacement of building stock would run over 100 years. In addition, old buildings have an essential role in term of their historic significance and their role in defining these great cities.
This paper sets out a plan to use Aquifer Thermal Energy Storage in conjunction with heat pumps across a large urban area in Central London as part of a carbon reduction masterplan. In essence it achieves this by utilising the different characteristics of the buildings and their uses to create a degree of balance between annual heating and cooling demands across the urban area as a whole. The capability of ATES to store heat energy is used to offset the varying demand load profiles over time.

The project is part of a larger carbon reduction profile being implemented by The South Kensington Cultural and Academic Estate, which has recently received supporting finance from the UK Treasury through the Department of Culture, Media and Sport (DCMS).
This paper sets out the strategy and methodology for the programme, which is starting now and will run over the next three years.

10 YEARS VDI 4640 – GERMAN GUIDELINES FOR GROUND COUPLED HEAT PUMPS, UTES AND DIRECT THERMAL USE OF THE UNDERGROUND

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VDI guidelines are generally recognized as engineering standards describing current and future state-of-the-art developments. Often they gain a special legal recognition for example through adoption by laws and regulations or through inclusion in terms and conditions of business and contracts. They are also used as basis documents and as national perspective in the drawing up of European or international rules. The market development of ground coupled heat pumps in the late 90ies was accompanied by developing technical guidelines compiling environmental aspects, basic requirements of components and installation techniques – the VDI 4640. These guideline consists of 4 parts dealing with different aspects and techniques of the thermal use of the underground:

1. Fundamentals, legal aspects and approvals, environmental aspects
2. Ground source heat pumps
3. Underground thermal energy storage
4. Direct uses

The first part of VDI 4640 describes the application of the mining law as well as the Water Management Act of the Federal States in connection with statutory state regulations and various

environmental aspects. Part two is dealing with ground source heat pumps using groundwater wells, horizontal loops and vertical boreholes as heat source. Basic rules for proper design, construction methods, testing procedures for components and system integration are described to ensure environmentally beneficial high quality products for the end-user. The third part focuses on design, construction and system integration of underground thermal energy storage in aquifers and borehole fields for heat or cold or combined heat/cold storage. Among the direct use of groundwater or borehole heat exchangers, energy piles etc. the earth-air heat exchanger plays an important role in the fourth part. The VDI 4640 guideline has been well recognized and widely used not only by designing engineers and installers but also by approval authorities.

PRACTICE AND TASK DEVELOPING UNDERGROUND THERMAL ENERGY STORAGE IN CHINA

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Energy storage technologies (EST) facilitate the efficient utilization of renewable energy sources and energy conservation, and they are expected to be more prevalent in the future. There is a great potential to substitute the use of EST for burning of fossil fuels by using stored heat that would otherwise be wasted and using renewable generation resources. These energy sources can be used more effectively through the addition of short and long term energy storage. Underground thermal energy storage (UTES) is one form of EST, and perhaps the most frequently used storage technology in North America and Europe. Gradually it is growing in China and Asia. But UTES systems involve complicated unsteady processes that include energy rejection, accumulation, preservation and extraction. This paper reviews the progress of UTES and emphasizes the basic problems for development in the future to supply a gap in the field of UTES in China. Meanwhile, the authors present a researching proposal and a demonstration researched, dealing with the investigation of mechanisms, characteristics and performance of the unsteady and transient heat transfer in a complex underground environment, and control strategies of the UTES system. Investigation of these problems will strengthen theoretical and practical understanding and facilitate more extensive application of UTES in China.

Wednesday 2:25-4:05
Session 5B
PCM/TCS/Solar Overviews

ICE THERMAL STORAGE AND LEED GOLD

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Storage is Nature's way to balance supply and demand and because we have essentially ignored this fact in the design of most of the buildings in the US, we have twice as many electric power plants as we really need. Ice Based Thermal Energy Storage Systems which cool buildings or process loads, have a long history around the world with over 6,000 commercial installations in 35 countries. By storing cooling at night, in the form of ice, and using it during the day to cool the buildings, major reductions in on-peak electric demand and energy costs are realized. This talk will demonstrate the basics of modern Ice based thermal storage systems and how they have been applied in numerous projects that have received the U.S. Green Building Council's LEED Gold Rating. Stored cooling allows the downsizing of chiller plant, without reducing redundancy or safety factor, reduced operating cost and energy use, and lower emissions at the power plants

IEA SOLAR HEATING AND COOLING PROGRAMME TASK 32: ADVANCED STORAGE CONCEPTS FOR SOLAR AND LOW ENERGY BUILDINGS

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Single family houses are the pioneer segment for low energy buildings. Low energy houses (40-45 kWh/m2 per year for space heating) combined with solar heat production are becoming more attractive to energy concerned persons, communities or authorities seeking to give a strong name to "sustainable development". Examples flourish in Germany with the "Passiv Haus" concept and in Switzerland with "Minergie", which captures already 10% of the segment of the new houses market. France is introducing the concept of "building with positive energy", that is producing more than it needs, in terms of heat and electricity.
High insulation standards, high quality glass and windows, heat recovery systems, and passive solar devices such as shading devices, help to decrease the need for heating and cooling to a low standard, 4 times less than what was the standard 20 years ago. However, an efficient and cost effective means for storing solar energy for heating during the winter months is still needed in low energy houses. The main goal of this "Task", part of the Solar Heating and Cooling Programme of the International Energy Agency (IEA), is therefore to investigate new or advanced solutions for storing thermal energy in systems providing heating or cooling for buildings. The ambition of the Task is not to develop new storage systems independent of a system application. The focus is on the integration of advanced storage concepts in a thermal system (solar, heat pump or boiler) for low energy housing. This provides both a framework and a goal to develop new technologies.

Wednesday 4:20- 6:00
Session 6A
Underground Thermal Energy Storage

EFFECTIVE THERMAL CONDUCTIVITY OF THE INSULATION OF HIGH TEMPERATURE UNDERGROUND THERMAL STORES DURING OPERATION

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High temperature seasonal heat stores for solar or waste heat applications require thermal insulation in order to minimize heat losses. The effective thermal conductivity of insulation materials increases with increasing temperature and moisture content. As the insulation of thermal stores is exposed to environmental influences the thermal conductivity and thus the heat losses are higher than the design values. Especially in the case of buried heat stores (tank and pit heat stores) the insulation can degrade due to increased moisture content caused by ground or surface water. The water content and thus the effect on the thermal conductivity mainly depend on the pore ratio and on the pore structure of the insulation. Using measured data gained with a guarded heating plate device a model for the thermal conductivity, based on the layer model of Krischer and Kast, has been developed. Particularly bulk insulation (e.g. expanded glass and expanded clay granules) has been investigated. An exponential increase of the thermal conductivity at high temperature even at low moisture content can be noticed.

The thermal conductivity of the insulation of two research pit heat stores operated at the Institute of Thermodynamics and Thermal Engineering (ITW) has been measured by means of heat flux and temperature sensors at different locations in the insulation. The comparison of the measured data with results of the layer model allows predictions about the current operation situation of buried heat stores with respect to the moisture content of the insulation.

Due to increased moisture content of the insulation, the thermal conductivity is particularly at high operation temperature significantly higher than the design values, thus causing higher heat losses. The design of wall systems of buried heat stores has to ensure that the insulation is protected from moisture from the interior and from the ambient or soil, respectively. Additionally the wall construction must guarantee that desiccation in case of wet insulation can take place.

PE-X BOREHOLE HEAT EXCHANGERS FOR HIGH TEMPERATURE UTES APPLICATIONS

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Seasonal storage at temperatures up 90 °C is an important component within large solar district heating plants. Because of promising geology, economy and technical advantages borehole storage was applied in several cases. Borehole heat exchangers (BHE's) made from PP (polypropylene) or PE-RT (polyethylene) may be selected for maximum fluid temperatures up to 75 °C. Seasonal storage in combination with solar collectors, biomass and cogeneration often exceed this temperature level. Only two polymers fulfill the basic requirements with respect to sufficient heat aging properties, flexibility and reasonable costs – PB (polybutylene) and PE-X (crosslinked polyethylene). While in the past PB was used in high temperature seasonal storages (solar district heating plants in Neckarsulm and Attenkirchen (Germany), Mol (Belgium) for industrial waste heat) the first installation in North America – the solar district heating plant in Okotoks, Canada – uses PE-X for BHE's.

The material properties of major interest for piping in high temperature BTES applications are:

- Resistance against internal pressure at elevated temperatures (life expectancy)
- Resistance against external action
- Minimized joint failure probability

PB and PE-X show a similar high life expectancy (>100 a) which is mainly determined by the annual operation hours at temperatures significantly above 90 °C. Fortunately, slow crack growth correlates directly to the results of the full notch creep test (FNCT) as described in ISO/FDIS 16770. The FNCT defines the time until a specimen notched according to this standard fails. In this respect PE-X shows massively superior resistance against external action compared to PB. Joint failures can hardly be avoided unless you avoid the joint. A significant advantage of PE-X is the possibility of bending the down-hole U-turn instead of using welding joints which are necessary for PB BHE's. These PE-X BHE's have been successfully installed at several sites in Europe; the first realized plant in North America is in Okotoks, Canada.

THE ROLE OF THERMAL ENERGY STORAGE SYSTEMS IN SUSTAINABLE DEVELOPMENT

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Thermal energy storage (TES) systems are examined from the perspectives of energy, exergy, environmental impact, sustainability and economics. Reductions possible through TES in energy use and environmental pollution levels are discussed in detail and highlighted with an illustrative example. The importance of using exergy analysis to obtain more realistic and meaningful assessments than the conventional energy analysis of the efficiency and performance of TES systems is demonstrated. The results indicate that cold TES can play a significant role in meeting society's preferences for more efficient, environmentally benign, sustainable and economic energy use in various sectors, and appears to be an appropriate technology for addressing the mismatches that often occur between the times of energy supply and demand.

PREHEAT: POLICY REINFORCEMENT FOR HEAT STORAGE TECHNOLOGIES IN EUROPE

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Heat storage can greatly improve the performance of renewable energy systems and of systems for rational use of energy, such as solar collectors, heat pumps and micro cogeneration.

A final breakthrough for renewable energy systems (RES) and rational use of energy (RUE) is inhibited by the current stagnation of research and development funding for heat storage technologies. The development and application of heat storage technologies need a coordinated and programmed approach on an international level, with long-term objectives and funding.

The basis for a programmed approach is the awareness with policy makers and key industrial players of the present state and future potential of heat storage technologies.

The recently started PREHEAT project, funded by the EC, aims to create this coherent international approach of heat storage technologies RD&D. The main dissemination actions of the project are aimed at:

- raising the awareness and knowledge of policy makers and decision makers of the economic and environmental potential of heat storage technologies
- initiating a heat storage community from the diverse and large number of companies working in the field of heat storage technologies

In the presentation an overview will be given of the present state of heat storage technologies and the field involved and of the planned actions in the PREHEAT project with their expected impact.

Wednesday 4:20- 6:00
Session 6B
Solar Applications

MONITORING RESULTS AND OPERATIONAL EXPERIENCES FOR A CENTRAL SOLAR DISTRICT HEATING SYSTEM WITH BOREHOLE THERMAL ENERGY STORE IN NECKARSULM (GERMANY)

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The solar assisted district heating system with borehole thermal energy store (BTES) in Neckarsulm is being realized since 1997. In 2005 about 300 accommodation units, a school with gymnasium and a shopping centre were supplied with heat by the district heating system. So far 5263 m² of solar thermal collectors are installed; the volume of the BTES is presently 63,360 m³ of ground volume. Solar heat is stored in the borehole thermal energy store from summer to winter. The BTES was extended twice; the operation of the first and second extension started in 1999 and in 2002, respectively. The maximum temperature in the borehole thermal energy store is expected to be about 85°C. In 2002 and 2003 a solar fraction based on the total heat demand (space heating and domestic hot water) of 39% was reached, while it was 34% in 2004. The planned solar fraction of 50% is expected to be reached within the next years. This paper presents an overview of the present status of the system as well as operational experiences.

EXPERIMENTAL INVESTIGATION ON A COMBINED SENSIBLE AND LATENT HEAT STORAGE UNIT INTEGRATED WITH SOLAR WATER HEATING SYSTEM

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Effective utilization of time-dependent energy resources relies on appropriate energy storage methods to reduce the time and rate mismatch between supply and demand. Thermal Energy Storages (TES) provide a high degree of flexibility since a variety of energy sources such as solar energy, industrial waste heat, heat pumps and off-peak electricity can be utilized, either combined or separately. This paper presents the experimental investigation of the thermal performance of a packed bed combined sensible and latent heat thermal energy storage unit integrated with solar collector. The TES unit contains paraffin as Phase Change Material (PCM) filled in spherical capsules, which are packed in an insulated cylindrical storage tank. The water used as Heat Transfer Fluid (HTF) to transfer heat from the solar collector to the storage tank also acts as sensible heat storage material. Charging experiments are carried out at varying inlet fluid temperatures to examine the effects of porosity and HTF flow rate on the performance of the storage unit. The performance parameters like instantaneous heat stored, charging rate and system efficiency are studied. Discharging experiments are carried out by both continuous and batchwise processes to recover the stored heat. The performance of the present system is compared with the conventional sensible heat storage system and the results are reported.

FIRST LARGE-SCALE SOLAR SEASONAL BOREHOLE THERMAL ENERGY STORAGE IN CANADA

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Most population centers in Canada receive a significant amount of solar radiation – more, in fact, than some countries such as Germany, Italy and Japan, where use of solar energy is becoming common; in particular, southern Alberta receives only slightly less than such areas as Arizona and Israel. This relatively high availability of solar energy has recently led to annual growth rates of 30 – 40% in sales of solar energy equipment in Canada – although only a small portion of this equipment is used for space heating. However, due to Canada's geographic location and climatic conditions, the bulk of the solar radiation is received in the summer months, and is relatively low during the winter months, when the demand for space heating reaches a peak. The ability to effectively store thermal energy for a period of months provides an opportunity to substantially increase the use of solar energy in Canada.

A large-scale solar seasonal storage project is currently in the early months of operation in Okotoks, Alberta. The Drake Landing Solar Community (DLSC) is a community of fifty-two modern detached homes that derive most of their heat requirements from solar energy, using borehole thermal energy storage (BTES) to store heat collected in the summer, for use in the winter. DLSC is the largest seasonal thermal energy storage system of its kind in North America and is designed to have both the highest annual solar fraction (90%) and the highest peak storage temperature (80°C) of any solar-based seasonal storage system in the world. Thermal energy is stored in 35,000 m^3 of soil and rock under a corner of the neighborhood park; the heat is transferred to and from the earth by water flowing through U-tubes in 144 boreholes, each 35 meters deep.

One of the noteworthy aspects of the DLSC project is that a single design team was responsible for the complete energy system, from energy collection, through storage, transport, conversion and final use. This allowed a much wider scope for optimizing overall system performance than is generally available in energy system design, where it is common to have separate sub-systems designed independently, with each design group responsible only for optimizing their portion of the total system.

As of the date of this paper, the heating system is in operation, delivering heat to those homes which have been occupied. Construction of the remaining homes and garages continues; the remaining solar collectors will be installed as the garages are completed.

Thursday 8:30-10:10
Session 7A
UTES- Borehole Performance

EXPERIMENT AND NUMBERICAL ANALYSIS OF THE DISCONTINUOUS OPERATION FOR GROUND HEAT EXCHANGERS

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The performance of the ground source heat pump (GSHP) used for earth energy requires an account for the operation mode, such as the continuous operation and the discontinuous cyclical operation (intermittence) due to the character of restorable temperature in the ground. Considering the fact that a heat pump system normally does not operate continuously all time in many countries, like China, for saving energy, the intermittent performance should be more suitable for cooling or heating system of the GSHP. In the present research, the effects of the intermittence and its recoverable temperature characteristics on the ground heat exchanger (GHE) are particularly studied. The operating experiments and numerical predictions are carried out. It is found that the temperature variations in the ground were related to the intermittent time, and then the intermittence prolonged the process of heat transfer between the working fluid and the borehole. It could also increase the heating/cooling capacity. An effective control of discontinuous operation mode can optimise the efficiency of GHEs so as to achieve better application of the earth energy. The control of the intermittent process can decrease the number of ground heat exchangers and ensure a lower first cost.
Keywords: ground source heat pump, discontinuous operation, intermittent process, renewable energy

DEVELOPING WORK ON GROUND HEAT EXCHANGERS

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Ground couple heat pump performance is to a great extent depending on the GHEX (Ground Heat Exchangers), the ground loop. The conventional GHEX for vertical bore holes looks as a U when it is installed in the ground and therefore called a U-loop. In order to improve thermal performance expressed in terms of W per installed boreholes meter sometime double U-loops are installed in the borehole. However, a conventional U-loop doesn't utilize the investment that the borehole constitutes in the very best way. It has to operate at high mass flow, i.e. turbulent flow, in order to offer high heat transfer performance from the fluid in the pipe to the ground. High flows means high pump losses and hence electric consumption. If the GHEX could operate with lower flows, preferably in the laminar flow regime the pump losses could be reduced considerably. Further more, in the conventional U-loop there is a heat transfer between the flow upward and the flow downwards which reduce heat transfer from the fluid in the U-loop to the ground.

There are new ideas coming up regarding more efficient GHEX. The most promising type of GHEX seams to be a type that is often called coaxial pipe. This paper describes a recent developing work on such type of coaxial GEHX, which is also characterized by having one of the legs thermal insulated.

STUDY ON GHP SYSTEM WITH A VERTICAL EARTH PIPE HEAT EXCHANGER: DEVELOPMENT AND VALIDATION OF NUMERICAL MODELS FOR GEO HEAT EXCHANGERS (DOUBLE U-TUBE TYPE AND DOUBLE-WALL TUBE TYPE)

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In Japan, the concept of geo heat pump systems began to attract interest from around 1980 as an energy-efficient technology, and the use of such systems has increased in recent years as concerns about environmental conservation have heightened. To promote the use of geo heat pump systems in Japan, it is essential to prepare sufficient engineering data and tools for predicting and evaluating system performance, while reducing the initial cost.

The performance of a geo heat pump system depends largely not only on the heat exchanger's heat extraction and injection of efficiencies, but also on the heat pump's operating performance characteristics and the load profile of the building. To predict and evaluate the system's operating performance, it is necessary to consider the interrelated actions of three factors: the geo heat exchanger's performance characteristics, the heat pump's performance characteristics and the building's load profile.

However, many of the engineering support tools for geo heat pump systems do not consider the temporal aspect of the building's load profile and the heat pump's operating performance, making it difficult to quantitatively predict the performance and effectiveness of the installed system.

Our ongoing study on geo heat pump systems aims to quantitatively predict the performance and effectiveness of the installed system, and thereby to provide guidance on appropriate operation and control schemes. To do this, we require an analysis model that can simulate the thermal behavior of a geo heat exchanger in consideration of the building's load profile and the heat pump's performance profile. This paper reports on our development of transient analysis models that simulate the geo heat exchanger's performance and our validation of these models through a comparison with the operation records of a system installed in a building.

THERMAL RESPONSE TEST – POWER INJECTION DEPENDANCE

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Thermal Response Test (TRT) is used to evaluate ground thermal properties for borehole heat exchanger (BHE) systems. During such tests, energy is injected or extracted by circulating a heated or chilled fluid in the BHE collector. The thermal response is measured and the design parameters, bedrock thermal conductivity and borehole thermal resistance, are determined. In Scandinavia groundwater-filled boreholes are used. The energy injected into the BHE results in a temperature gradient in and around the borehole, causing natural convection in the groundwater. The size of the convective heat transfer will depend on how fractured the bedrock is, energy injection, size of borehole and collector and undisturbed ground temperature. For a BHE system with both heat and cold mode this could mean different borehole thermal resistance and effective conductivity for different seasons. In determining design parameters for such systems a single TRT measurement with heat injection is often used. Since the thermal response in these tests depends on the conductive and convective heat transfer this implies that test results will depend on the injected effect. The evaluated data are therefore only certain for that injection rate and design of combined systems ought to be with differing resistance for different modes. Luleå University of Technology has recently acquired a new TRT device (TEDhc) which has the ability to inject both heat and cold. Investigation of the convective heat transfer has started with this new equipment. Several heat injections measurements have been conducted in a test borehole at campus. Depending on injected power and water temperature, evaluated design parameters differ in results. The effect of the convective heat transfer is clearly visible on the borehole thermal resistance, where higher temperature results in lower thermal resistance.

Thursday 8:30-10:10
Session 7B
Solar cont'd and Floor TES systems

THERMAL WIND SOLAR POWER PLANT AS A SOLUTION OF THE ENERGY SECURITY SUPPLY PROBLEM ON ISLANDS

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The study presents possible innovative solutions for the problem of intermittency and new ways to increase the penetration of the wind energy and other renewable energy sources (RES) on small electrical grids.
The solution is a new concept of power plant, a thermal wind solar power plant (TWSPP): the wind energy converters are interconnected with two heat-pump systems, one of the heat-pump system extracts heat from an insulated compartment (the cold source); and another heat-pump system transfers heat from the soil, the thermal energy of the oceans, or the thermal energy of the groundwater to the hot source of the plant. This setup works as a conventional power plant. The main items of the power station are: heat pumps, heat - exchangers, condenser systems, turbo – generator, and the auxiliary systems.
The TWSPP works 24 h per day, with stable voltage, and frequency, and constant power output, under a mature energy control system.

STUDY ON A FLOOR SUPPLY AIR CONDITIONING SYSTEM WITH THERMAL ENERGY STORAGE USING GRANULATED PCM

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We have proposed a new floor supply air conditioning system for office buildings, using granulated phase change material (PCM) to augment building mass thermal storage. Cold energy is stored in both the PCM and the building mass in the nighttime using cheaper power rates and discharged to the room space in the daytime. The system would cover the whole cooling load by thermal energy storage without typical large tanks of ice or water.
A demonstration system is constructed in order to evaluate the effect of load shifting to the nighttime and thermal environment quantitatively in the proposed system.
Calculations intended for the environmental testing room of 9.2m2 predict that the whole cooling load can be covered by discharged cold energy storing during night without operation of air conditioners during the daytime in conditions of supply air temperatures in the under floor space around 12 to 13ºC.
Next, an experiment in the testing room with a supply air temperature of 12.5ºC on average can result in completion of load shifting. The authors confirmed that the calculation give good agreement with the experiment under the similar operating conditions with respect to stored heat in the nighttime and the floor and room air temperatures in the room space.
The results of thermal sensation votes from 4 subjects don't show neither "cold" nor "uncomfortable" sensations for both the whole body and each part of the body even in the morning. It is found that the proposed system using the granulated PCM can improve the uncomfortable coldness especially near the floor in the previous systems.

ENERGY MANAGEMENT OF A CHILLED WATER PLANT USING THERMAL STORAGE

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This paper illustrates a project implemented in a major IBM plant in Canada using a TES system integrated with other technologies to optimize the chilled water production. The implementation of the Novanergy system (thermal storage with phase change material) has given important peak load reductions as well as significant reduction in the energy consumption and in the environmental impact of the chilled water system operation. A load-leveling approach has been exploited to minimize the required equipment and storage capacities (reducing the amount of refrigerant needs by about the equivalent of a 1000 tons unit) for a given load because of energy efficiency improvement.

The total electric savings were 5,312 MWh. The dollar value of the savings at a marginal cost of $0.0253 was $134,400. Additional savings from peak load shaving (kW) was $162,400 for a grand total of $296,800. The present value of the project over twenty years is equal to $3.9 million dollars. The project has demonstrated an important improvement of the chilled water system using thermal storage as well as a reduction of about 35% in GHG emission for the production of chilled water.

PRACTICAL DEVELOPMENTS IN SENSIBLE HEAT, DIURNAL COOL THERMAL ENERGY STORAGE (TES):LARGE APPLICATIONS, LOW TEMPS, ENERGY EFFICIENCY, AND OPERATING PLUS CAPITAL SAVINGS

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Several significant recent trends and developments in the widespread practical application of sensible heat, diurnal, cool Thermal Energy Storage (TES) are presented and discussed.

- In particular, an increasing number of large capacity applications are evident. The types of large applications include campus cooling networks, private industry, and District Cooling utility developments, where TES provides demand management for energy users, as well as Turbine Inlet Cooling (TIC) for hot weather power enhancement of gas turbine-based electric power generation plants.
- Systems are often being designed for lower than traditional supply temperatures, or dual-designed for initial conventional supply temperatures as well as for lower future temperatures with higher storage capacities.
- Energy efficiency of TES systems, both on-site at the energy user and at source energy power plants, is explored.
- Economics are examined to document how large TES installations, when applied at times of either new facility construction or chiller plant capacity expansion or rehabilitation, often provide not only major operating cost benefits but even dramatic capital cost savings versus conventional (non-TES) chiller plant capacity.

Actual TES Case Histories are used to demonstrate each element of the paper.

Thursday 10:35-12:15
Session 8A
UTES- Borehole Performance

SEVERAL EXAMPLES OF UTES IN THE US

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Underground Thermal Energy Storage in the US has primarily been associated with geothermal heat pump (GHP) systems. With few exceptions, significantly more heat is injected into the ground than extracted for other than single family houses and small commercial buildings over an annual cycle. Design engineers typically consider this as resulting in thermal interference between boreholes and size a BTES system to dissipate the excess heat. However, many designs ignore long-term thermal storage effects. This paper explores the importance of designing thermally balanced UTES systems. Several realized and currently designed BTES and ATES systems are discussed demonstrating the benefit to the ecology, efficiency and economy of thermally balanced UTES systems.

THERMAL STUDY OF A LARGE GROUND HEAT EXCHANGER IN CLAY SOIL IN THE COLD WEATHER ENVIRONMENT OF NORTHERN USA: SOME INITIAL FINDINGS

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To study the effect of long term temperature drift in ground heat exchangers (GHX) and the degree to which the GHXs are able to gain heat from the boundaries, temperatures at some key points in a GHX recently built in the campus of the University of North Dakota at Grand Forks is currently being monitored. The GHX under study consists of 212 bore holes each 45.7 m (150 ft) deep drilled in tight clay/ silt formations with little ground water flow. The thermal reservoir around each borehole is a square cylinder and the vertical faces of the cylinder form an adiabatic surface. The monitoring points are located in these planes well inside the top half of the GHX. Initial results of the study have been compared with undisturbed earth temperature data obtained from a nearby site at nearly identical depths. The initial results over first 100 days covering nearly the entire winter season of 2005/2006 indicate that at the deeper observation points, the forcing due to the heat extraction from the boreholes has the dominant effect vis-à-vis the atmospheric forcing. Though under atmospheric forcing alone, temperatures at these depths should have indicated a warming trend during the reference period, the temperatures at these points exhibit a persistent cooling trend. However a little above (2.7m), the cooling rates are steeper as the atmospheric forcing and the engineered forcing mutually reinforces each other. It is concluded that these points of observation are appropriate, and any long term trend of the annual mean temperature at these points of observation would be indicative of the long term temperature drift due to the net heat extraction from the thermal reservoir.

HEAT TRANSFER EXPERIMENT IN THE GROUND WITH GROUND WATER ADVECTION

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We have performed laboratory experiments in order to investigate the effect of ground water flow on heat transfer in the ground and improve a tool for the ground source heat pump system we developed to evaluate the effect. The apparatus features to imitate ground water flow in the sand filled layer into the apparatus. A probe which can generate constant heat was buried in the sand filled layer. Temperatures of the probe and each point in the sand filled layer were measured.

First, the experiments were carried out for several times by changing the ground water flow. As the result, it was identified that when the effective thermal conductivity of the ground is estimated by applying the line heat source theory, the variation of the effective thermal conductivity for elapsed time depends on the ground water velocity

Next, it is clear that the variations of the thermal responses calculated by moving line heat source theory produce good agreement with measured one, it is confirmed that applying moving line heat source theory for calculation of the ground temperature with ground water flow is effective.

In final, method of estimation of the ground water velocity applying the moving line heat source theory was proposed. It was indicated that the method is useful for the estimation of the ground water velocity from the results of the examples.

Thursday 10:35-12:15
Session 8B
PCM materials

PCM-GRAPHITE COMPOSITES FOR HIGH TEMPERATURE THERMAL ENERGY STORAGE

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Latent thermal energy storage systems use the heat absorbed during melting and released during solidification of phase change materials (PCMs). From an energy efficiency point of view, PCM storage systems have the advantage that they operate with a small temperature difference between charging and discharging of the storage. Also, these storage systems have high energy densities compared to sensible heat storages assuming such energy efficient operation. PCMs considered for temperatures between 100 and 300°C are mainly anhydrous salts. Applications include industrial process heat utilisation and solar power generation using direct steam technology. However, there are heat transfer limitations on the storage design due to the low thermal conductivity of the salts. Major approaches to overcome this inadequate heat transfer are the enlargement of the heat exchanger surface or the use of composite latent heat storage materials (CLHSM). This work selects the latter, where the properties of the high latent heat of the PCM and the good thermal conductivity of graphite are combined. As a PCM, this work uses the equimolar composition of potassium nitrate (KNO3) and sodium nitrate (NaNO3) with a melting temperature of about 220°C. There is a variety of potential preparation routes for CLHSM and these processes have a decisive impact on the interconnectivity of the graphite. Generally a highly interconnected graphite matrix is desirable in order to achieve a high effective thermal conductivity. We present in this paper the preparation of CLHSM from graphite and the eutectic KNO3-NaNO3 by the compression and the infiltration route using natural graphite flakes, ground expanded graphite particles and compressed expanded graphite plates. This results in composites with a different level of interconnectivity of the graphite. The composites are characterized in terms of their effective thermal conductivity as a function of temperature using the laser-flash method. The impact of thermal cycling on the effective thermal conductivity, segregation, form stability and expansion of the CLHSM is also discussed. The CLHSM show a considerable enhancement of the thermal conductivity compared with those of the single PCM.

BINARY MIXTURES OF PARAFFIN AND FATTY ACIDS WITH SODIUM ACETATE TRIHYDRATE TO BE USED AS PHASE CHANGE MATERIALS

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Most of the researchers who worked with fatty acids and paraffins focused on experimental studies to show the possibility to use them as phase change materials (PCM), determining the eutectic point of their binary mixtures and using them in building materials. Major drawback of fatty acids and paraffins is their low thermal conductivity. The purpose of this study is to find new alternative PCM mixtures with favorable thermal characteristics. Analytical grade paraffin (Merck) and different fatty acids (stearic, palmitic, myristic, and lauric acid) were mixed with sodium acetate trihydrate ($CH_3COONa \cdot 3H_2O$), to determine the possibility of using them as phase change materials for thermal energy storage. There is no present work on the mixtures of fatty acids - sodium acetate trihydrate and paraffin - sodium acetate trihydrate. The experiments to determine the thermal characteristics of the mixtures are on-going and results will be presented in the final paper.

Thursday (and Friday)12:15-2:15
Session 9A
Topics in Underground Thermal Energy Storage

CASE STUDY OF A BTES AND ENERGY PILES APPLICATION FOR A BELGIAN HOSPITAL

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The Flemish health sector is characterized by a high, constant and simultaneousness heating/cooling demand. Since recent years the cooling demand has tremendously increased due to higher internal heat production of medical equipment and comfort requirements in patient and consultation rooms. Therefore the health sector is continuously searching for energy-efficient cooling/heating production/distribution techniques. The Flemish government has recently adopted several energy saving recommendations for new and renovation projects in the health sector. In recent years VITO carried out several case studies on ground-coupled heat pumps with vertical borehole heat exchangers (BHEs) in the health sector. In this paper a case study of a BTES application in a large new build hospital in Flanders is presented. The technical, economical and ecological feasibility of BHEs and energy piles in combination with a ground-coupled heat pump was evaluated. In the near future this project will be realized.

The hospital has 600 beds with a total heated/cooled floor surface of 59.000 m². The total heating load was calculated as 4,5 MW; 2,6 MW as total cooling load. Based on the energy simulations and a technical (and economical) evaluation a total of 688 energy piles at a depth of 12 m and 60 BHEs at a depth of 120 m can be installed. With 30% of the total cooling load the energy piles and the BTES application can deliver 78% of the yearly cooling energy demand. This cooling demand is indeed produced at a high SPF of 19 (higher then classical chillers). From an economic point of view the installation can save € 30.000 per year on the total operational costs (energy and maintenance costs) in comparison with a classical cold and heat production (chiller and gas-fired boilers= reference installation). A simple pay-back period of 11 years can be realized. With the BTES application the hospital can produce cold and heat at a high efficiency and on a sustainable and energy-efficient way.

A DESIGN AND PERFORMANCE PREDICTION OF THE GROUND SOURCE HEAT PUMP SYSTEM AT SOEN CAMPUS OF SAPPORO CITY UNIVERSITY

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The authors introduce the outlines of designing, performance prediction and feasibility study, and process of construction related to a ground source heat pump (GSHP) system using steel foundation piles as the ground heat exchangers in this paper. Sapporo City University will be founded in April 2006 and a new building of the Soen campus will be installed a GSHP system with steel foundation piles as ground heat exchangers for a part of the heating.

First, the authors determined that heating output of the GSHP system is corresponded to heat load from ventilation of the building. Allowable heat supply from the GSHP system was evaluated by using the design tool for the GSHP system under the condition that the minimum outlet temperature from the heat pump unit wouldn't drop under -2ºC. The result showed that the GSHP system could supply daily base heating load of 40 kW. However, heating output of 50 kW is at least required to claim the subsidy from the Japanese Ministry of the Environment. Therefore, daily base heating load is raised from 40kW to 50kW and the rest is covered by three borehole heat exchangers of 75m long with single U-tube.

Next, a performance prediction and feasibility study were carried out with the tool. The results show that heating output of the GSHP system with 51 steel foundation piles of approximately 4.7 m long and three borehole heat exchangers of 75 m long is enough to cover base heating load of 50kW generated by ventilation of the building. In addition, the GSHP system is expected to reduce annual CO_2 emissions of 4.0 / year in comparison with a gas boiler system.

In final, the construction of the GSHP system was done basis on the design by the tool we developed. The construction work was finished in February 2006 and the GSHP system has been operated since April 2006.

EVALUATION OF UNDERGROUND ENERGY STORAGE PERFORMANCES IN BELGIUM

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In this paper, we will investigate the ground storage of solar energy by numerical simulations. This geothermal underground heat storage is part of a solar combisystem including solar collectors, an underground heat exchanger located under the house slab and a heat pump. The underground heat exchanger allows to store energy from the solar collectors and to extract energy through the heat pump in order to heat the house. Buildings, solar collectors, heat exchangers and heat pumps are equipments which are easy to model; whereas, the thermal behavior of the soil (which constitutes here the storage medium) is not yet very well known and requires further modeling developments. Soils are porous media mainly composed of solid materials, water and air. They are not homogeneous and most of the required properties are moisture content and temperature dependent. The main objective of this study is the modeling of heat and moisture transfer in soils in order to evaluate the performances of a "seasonal" storage of energy.

We have developed a one dimensional conductive model of the soil which takes into account the effect of water content on the soil thermal properties. We consider the water content only depends on the water table depth. This model allows the estimation of the system performances (storage efficiency and solar fraction of the heating system). The evaluation of the heating demand of the building is made using a simple model of resistances and capacities. The solar collector is modeled by a capacity curve and the heat pump by a correlation relating its performances to the temperature difference between soil and inside atmosphere. Different parameters have already been tested: two compactness of the house (volume to heat losses surface

ratio) with respectively 150 and 75 m² underground heat exchanger, two tube step of exchanger, and different solar collector surfaces. The studied house has an annual heat demand of around 65 kWh/m².

The first simulations show a light effect of the solar collector surface on the storage performances, a positive effect of a high water table depth and a positive effect of the moisture content. In comparison to an equivalent installation of a classical ground coupled heat pump (without solar collector), this combisystem seems to be less effective.

UTES POTENTIAL FOR SPACE HEATING AND COOLING IN LIBYA

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Libya's climate is dry and warm with annual mean temperatures from 15oC to 25oC, with a temperature difference of 20oC between the coldest and warmest months. The Mediterranean coast and the Sahara Desert are the country's most prominent natural features. Heating is needed during the short winter and there is a large cooling demand during the long summer. Since the undisturbed ground temperature is equal to the annual mean air temperature the ground is warmer than the air during the winter and colder than air during summer. This is what is required for the direct use of the ground for heating and cooling. In such ground coupled heating and cooling systems and in storage systems, Underground Thermal Energy Storage (UTES), some kind of underground duct system is used to inject or extract heat from the ground. The duct system could be placed horizontally or vertically (e.g. in boreholes) in the ground. In many cases heat pumps or cooling machines are included in the systems but in favorable cases, such as in the North African climate, the ground can be used directly for heating and cooling. Then, only a circulation pump is used to pump water through the underground duct system with high efficiencies. Such systems can also be used for thermal energy storage, during shorter periods (diurnal) or even between the seasons. In September 2005 Libyan-Swedish collaboration started to develop and implement UTES systems in this region. Sweden has considerable experience in ground coupled systems, theoretically and practically, and there are presently more than 300,000 systems in operation in Sweden, mainly for heating. Most of these are small-scale heating systems for singe-family houses but during the last decade several hundred large-scale systems have been built for heating and cooling of commercial buildings. The ongoing collaboration will also consider local traditions and systems for cooling with the aim of combining traditional methods with ground coupled heating and cooling systems. This PhD work includes simulation, testing, design, construction, and operation of such system in Libya. Planned and ongoing work is outlined in this paper.

ENHANCEMENT OF AN INTEGRATED SIMULATION TOOL FOR GROUND-SOURCE HEAT PUMP SYSTEM DESIGN AND ENERGY ANALYSIS

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eQUEST is becoming the most popularly used building energy analysis tool in the US. It combines easy-to-use building model creation wizards, graphical results display, intelligent input defaults, and the up-to-date DOE-2 (version 2.2) simulation engine. However, due to limitations of previous DOE-2 in modeling the ground loop heat exchanger (GLHE) and lack of a convenient procedure to build ground source heat pump (GSHP) systems with eQUEST, the usage of eQUEST for GSHP system simulation and design has been significantly restricted. It is highly desirable that the GSHP simulation capabilities of eQUEST can be improved to facilitate the design of GSHP systems and reveal the energy saving benefits resulting from the GSHP systems.

In this paper, new improvements and features of the GSHP system simulation in eQUEST are presented. The major improvement is integrating an advanced GLHE model into DOE-2, which employees a sophisticated algorithm to calculate the borehole thermal resistance and uses the g-function approach to account for heat transfer characteristics of various borehole field configurations. In addition, a dedicated wizard with informative design tips and material database has also been implemented to help users build GSHP systems conveniently.

Verification and validation results show that the new vertical GHX model implemented into eQUEST/DOE-2.2 matches well with more sophisticated and validated model. The enhanced eQUEST/DOE-2.2 is able to correctly predict responses of GSHP system to changes of GHX design. It is therefore a very useful tool for GSHP system design.

Thursday (and Friday)12:15-2:15
Session 9B
Topics in Underground Thermal Energy Storage

SNOW MELTING PERFORMANCE OF GROUND SNOW MELTING TANK

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The city of Sapporo is located in the northern part of Japan and has a lot of snow over 5 m high every year. Removed snow from the road ways is generally transported by trucks to temporary dumping sites in the suburbs. The transport needs huge costs and may cause increase of CO_2 emissions. Therefore it is important to pay attention to onsite snow removal measures now, which are expected to be low cost and environment-friendly. Then the authors propose the Ground Snow Melting Tank (GSMT) made of hollow steel piles, in which ground thermal energy is utilized directly for snow melting without the use of fossil energy resources.

Laboratory experiments intended to improve the snow melting performance in the GSMT are conducted with a cylindrical pipe of 100 mmϕ. Water supplied from a nozzle on the bottom of the cylinder causes rotating movement under appropriate conditions. It is found that the water movement is effective to improve the snow melting performance against a small amount of snow.

Field experiments are conducted with a GSMT of 1200 mmϕ and 16.3 m long in order to evaluate the maximum performance of snow melting. The snow melting performance is confirmed quantitatively by the experiments, in which snow is shoveled every 3 to 4 days periodically and nearly filled in the GSMT during the experiment. The result shows that the total amount of snow melting reaches around 13 tons for 41 days.

The performance on snow melting measured in the experiments agreed well with results from a theoretical calculation which shows the maximum performance. This theoretical method can be utilized for evaluation of performance of the GSMT in case where snow is filled in the GSMT throughout the period.

Feasibility of the GSMT for roadways and residential houses is investigated by using the theoretical calculation. It predicts that the amount of snow to be cleared from one corner of a two-lane roadway or six residential houses can be melted by two GSMTs with 30 m long and a diameter of 1200 mmϕ.

PHASE CHANGE MATERIAL BASED THERMAL STORAGE FOR ENERGY CONSERVATION IN BUILDING ARCHITECTURE

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Efficient and economical technology that can be used to store large amounts of heat or cold in a definite volume is the subject of research for a long time. Thermal storage plays an important role in building energy conservation, which is greatly assisted by the incorporation of latent heat storage in building products. Latent heat storage in a phase change material (PCM) is very attractive because of its high storage density with small temperature swing. It has been demonstrated that for the development of a latent heat storage system (LHTS) in a building fabric, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM. Thermal energy storage in the walls, ceiling and floor of buildings may be enhanced by encapsulating or embedding suitable phase change materials (PCMs) within these surfaces. They can either capture solar energy directly or thermal energy through natural convection. Increasing the thermal storage capacity of a building can increase human comfort by decreasing the frequency of internal air temperature swings so that the indoor air temperature is closer to the desired temperature for a longer period of time. This paper aims to submit the information on the developments of PCM incorporation in buildings for energy saving, the problems associated with the selection of phase change material and the various methods used to contain them for space heating and cooling applications.

OUR RESEARCH ON SHAPE-STABILIZED PCM IN ENERGY-EFFICIENT BUILDINGS

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Shape-stabilized phase change material (PCM) is a kind of novel PCM. It has the following salient features: high apparent specific heat for phase change temperature region, suitable thermal conductivity, keeping shape stabilized in the phase change process and no need for containers. The preparation for such kind material was investigated and its thermal physical properties were measured. Some applications of such material in energy efficient buildings were studied. Some models of analyzing the thermal performance of the systems were developed, which were validated with the experiments. The following conclusions are obtained: (1) the applications of the novel PCM we put forward are of promising perspectives in some climate regions; (2) by using different paraffin, the melting temperature of shape-stabilized PCM can be adjusted; (3) the heat of fusion of it is in the range of 62-138 kJ/kg; (4) for PCM floor or wallboard to absorb solar energy to narrow the temperature swing in a day in winter, the suitable melting temperature of PCM should be a little higher than average indoor air temperature of the room without PCM for the period of sunshine; (5) for the electric under-floor space heating system, the optimal melting temperature can be determined by simulation; (6) PCM layer used in the aforementioned application should not be thicker than 2 cm; (7) There are some critical values of shape-stabilized PCMs for free heating/cooling and with the available PCMs in a considered room the spacing heating/cooling time can be greatly delayed when compared with ordinary concrete room; (8) the models developed by us are helpful for applications of shape-stabilized PCM in buildings.

OPTIMAL DESIGN OF CHILLER UNITS AND COLD WATER STORAGES FOR DISTRICT COOLING SYSTEMS

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The presented results base on the study “feasibility evaluation for empowerment of CHCP by means of cool thermal energy storages in large supplying systems”. The study has been supported by Federal Ministry of Economics and Labour (BMWA), represented by Project Management Organisation Jülich (PTJ). Project partners are Utility Company Chemnitz (SWC) und Chemnitz University of Technology.

The goal of this project is the efficiency improvement of combined heat and cool and power cycle (CHCP) by means of Thermal Energy Storage (TES). The central topic of inquiry is the district cooling system of the city of Chemnitz. The examination deals with refitting the system by a TES. The increasing cooling demand because of more air conditioning in city buildings leads to extension of the system. SWC are looking for a favourable solution in both ecological and economic terms.

The usage of Cool TES in Europe especially in Germany is a relative new topic. Therefore the examination of feasibility and design is necessary. The demonstrated solutions base on the specific examination at Chemnitz district cooling system. But the solutions in the article are more general and can be adopt to other systems. The central questions are: How does the dimensioning of chillers and storages affect the evaluation marks? What are the ranges for an optimal system dimensioning? As a consequence of these first results the implementation of large TES in connection with better enforcement of CHCP is being striven.

NUMERICAL SIMULATION OF THE THERMAL BEHAVIOUR OF AN ENERGY STORAGE UNIT WITH PHASE CHANGE MATERIALS FOR AIR CONDITIONING APPLICATIONS BETWEEN 17 AND 40ºC.

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In this paper, the application of phase change materials (PCM) in air conditioning systems is studied. Using PCM in air conditioning systems can smooth daily fluctuations in room temperature by lowering the peak temperatures resulting from external daily temperature changes. PCM also reduce home heating or cooling loads producing energy savings for the consumer.

Another way to reduce consumption is using PCM in free-cooling systems; free-cooling is understood as a mean to store outdoors coolness during the night, to supply indoors cooling during the day. In this case, the use of PCM is suitable because of the small temperature difference between day indoors and night outdoors.

Four theoretical models are developed in order to simulate the thermal behaviour of macroencapsulated PCM (plate geometry) exposed to an air flow. The selected PCM are chosen because they perfectly fit in free-cooling applications as they have an appropriate thermal window. Both, organic and inorganic materials are studied. In each simulation case, enthalpy-temperature curves obtained in the laboratory with the T-history method are used.

Each of these four models takes into account different assumptions:

- Semi-analytical model; this model is developed starting from the air-
- PCM heat transfer equation and eventually discretizing the system.
- Finite differences model: one dimension implicit; in this model heat transfer inside the PCM only occurs in the direction normal to the air flow and it considers only conduction inside the slab.
- Finite differences model: two dimensions implicit; in this case both directions inside PCM (x and y) are analyzed.
- Fluid dynamic model; this model uses a CFD (Fluent) so convection inside the PCM or even gravity effect can be taken into account.

An installation that allows testing the performance of PCMs in such systems was used to obtain experimental data (it was designed and constructed previously). Experiments were performed following the design of experiments strategy.

Results obtained from the theoretical models and from the experiments were compared so the model which fits better can be chosen and conclusions can be taken.

THE ECONOMIC BENEFITS OF DIURNAL AND SEASONAL COOL STORAGE FOR UNIVERSITIES ON THE PJM SYSTEM

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There are many local benefits to providing cool storage for industrial, commercial and institutional entities. Usually they involve economies associated with O&M cost reduction (off peak pricing of electricity, optimal operational efficiencies of equipment) and reducing capital required to meet peak cooling system demand (by deferring or eliminating new chiller construction). PJM provides extensive economic (marginal and average pricing) information already available to utilities, customers and power marketing professionals on its website and soon hopes to publish environmental attributes of its generation units to supplement that. The variations in pricing throughout a single day during the summer peak demand period within the northeastern portion of the United States provides significant economic incentives to assure that adequately designed diurnal storage systems can provide significantly short paybacks. It is likely that seasonal storage, similar to that being developed at Richard Stockton State College to supplement its world-famous ground-source heat pump system[1], will also be able to take advantage of seasonally varying marginal prices available locally and across PJM. Many universities are already reaping the economic benefits of diurnal price fluctuations. This paper analyses and summarizes both the diurnal and seasonal economic benefits that can be achieved by well developed diurnal and seasonal storage technologies. Tabular as well as graphical results illustrate the benefits in terms and quantities that might prove useful to individuals and institutions considering diurnal and seasonal cool storage as a means to economically save on electric demand, infrastructure expansion through daily interactions with the PJM utility grid.

ADSORPTION SPEED AND MASS TRANSFER ZONE ANALYSIS OF WATER VAPOUR ON THE SOLID SORBENT MATERIALS ZEOLITE AND SILICAGEL WITH THE FOCUS ON THE HEAT EXCHANGER DESIGN

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The time and vapour pressure dependent adsorbed water vapour mass on a silicagel 490 and on a zeolite 13 X granular fixed bed was measured in a closed under vacuum working experimental set-up. In the same experiment the temperature development as a function of time t and depth z in the fixed bed was

measured as well. The length of the fixed bed was 15 cm and the cross section was $7.8x10^{-3}$ m^2. The average particle size of the silicagel 490 was 3 – 5 mm and for zeolite spherical particles of 1 mm average diameter were used. In the first 300 s the adsorption speed is $dm/dt = 2x10^{-2}$ g/s while from t > 300 s $dm/dt = 1.7x10^{-3}$ g/s on silicagel 490. On zeolite 13 X a $dm/dt = 3x10^{-2}$ g/s was measured for the first 400 s of reaction time and for t > 400 s the mass of water vapour adsorbed in function of time was reduced to $dm/dt = 5x10^{-3}$ g/s. A mass transfer zone (MTZ) of L = 5 – 6 cm and L = 1 – 2 cm was determined for silicagel 490 and zeolite 13 X, respectively. Related to the fixed bed cross section the power density for zeolite 13 X was 9.5 kW/m^2 and 6.4 kW/ m^2 for silicagel 490 at a water vapour pressure of p(T=22 °C) = 12.1 mbar. The power density in the sorption system directly correlates with the water vapour pressure p(T). Because the adsorption process on solid sorption materials is diffusion controlled and silicagel 490 and zeolite 13 X have a low heat conductivity a large mass and heat transfer area is needed in the sorption process. So, an aluminum rib heat exchanger with a rib distance of d(1) = 7 mm was built. The fluid carrying pipes of the rib heat exchanger where set to each other in a distance of L = 45 mm in the y direction and L = 60 mm in the z direction. For the application purpose in an adsorption heating system a temperature lift of up to T = 80 °C can be reached.

USE OF EXTERNAL VERTICAL FINS IN PHASE CHANGE MATERIALS MODULES FOR DOMESTIC HOT WATER TANKS

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The effect of using external vertical fins in Phase Change Materials (PCM) modules to improve the natural convection coefficient in water was studied in this paper. The use of PCM in a water tank working with a solar system allows storing a lot of energy, but it is necessary to transfer this energy to the water during demand. Heat transfer has been optimized in PCM composites and modules but not in the case of natural convection to the water. External fins increase the heat transfer surface and the heat transfer coefficient changes. An experimental work was designed and carried out to determine natural convection heat transfer coefficients for PCM cylindrical modules with two different external vertical fin geometries. Results were presented as a temperature variation over time of the PCM and the surrounding water, and the heat transfer coefficient as a function of the temperature difference for different fins. The results proved the technical potential of external fins for heat storage systems using PCM.

A PRACTICAL STUDY ON APPLICATION OF COMMISSIONING TO A DHC PLANT DURING THE OPERATION AND MAINTENANCE STAGE

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Increased in public awareness of the need to reduce environmental load has led to growing interest in efficient energy management strategies such as thermal storage systems. However, problems are likely to be encountered if a thermal storage system is installed without commissioning (Cx) to ensure that the system operates as intended. A thermal storage system consists of numerous machines, so the system requires Cx or at least "TAB" (Test Adjust and Balancing). In Japan, the importance of Cx or TAB is well known to engineers, but there are as yet few examples of their application.

PCM-ENHANCED CELLULOSE INSULATION THERMAL MASS IN LIGHTWEIGHT NATURAL FIBERS

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The objective of this paper is to present current developments in research on a new generation of cellulose insulation, which is expected to perform as a massive building component. A thermal mass effect is provided by specially tailored phase change material (PCM). During 2004/05 an Oak Ridge National Laboratory team developed and patented a new generation of cellulose insulation, which is thermally enhanced by addition of microencapsulated PCM. During 2005, the first specimens of the cellulose/PCM material were produced at a commercial pilot plant facility operated by Advanced Fiber Technology. A series of flammability tests were performed to ensure that a new material will not cause fire problems. The apparent thermal conductivity of the new material was tested in a heat-flow meter apparatus operated in accordance with ASTM C 518. Dynamic tests in a hot-box facility were also performed. Current results resulting from this project are discussed in this paper.

Thursday 2:15-3:55
Session 10A
UTES- Borehole Performance

Development of a Numerical Model to Predict Heat Extraction and Injection Rates of a Ground Heat Exchanger

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For the design of a ground-source heat pump (GSHP) system, it is necessary to accurately predict the heat extraction and injection rates of the heat exchanger. Many models that combine ground heat conduction and heat exchangers have been proposed to predict heat extraction/injection rates from/into the ground in the research field of heating, ventilation and air-conditioning (HVAC) systems. However, most of these models are based on a heat conduction model with cylindrical coordinates. In most cases the effect of the ground water flow is incorporated into the effective heat conductivities. There is a possibility that these models have an inaccuracy in their predictions for long periods. Furthermore, most of the proposed models utilize a cylindrical-shaped heat exchanger with the concept of an equivalent diameter and do not consider the effect of the exact shape of the heat exchanger. This model might cause numerical errors in the prediction. On the other hand, in the fields of hydrology, geology, and geotechnical engineering, simulation models of groundwater flow, mass and heat transfer in the soil have been developed. However, the purpose of these models has been to analyze macroscopic groundwater flow, mass and heat transfer in the soil; modeling of a ground heat exchanger is not supported.

In this paper, a numerical model that combines a heat transport model with ground water flow, and a heat exchanger model with an exact shape is developed. Furthermore, to obtain accurate simulation results, it is necessary to ascertain the soil physical-property values such as thermal conductivity, heat capacity and

hydraulic conductivity. Thus, the authors also propose a method for estimating soil properties based on ground investigations. Moreover, the validity of these methods is confirmed by comparing between simulation and experimental results. Finally, to estimate the influence of the physical properties of the soil such as the ground water flow speed and heat conductivity, and the heat capacity of the soil, sensitivity analyses under various soil properties are conducted.

QUALITY REQUIREMENTS OF A THERMAL RESPONSE TEST

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Ground-coupled systems design requires good knowledge of the ground thermal properties and the heat-transfer efficiency of the borehole heat exchanger (BHE), in order to guarantee an efficient and economic operation. For this purpose the Thermal Response Test (TRT) procedure was developed in 1996 at the Oklahoma State University (USA) and the Technical University Lulea (SE). This test procedure evaluates the temperature response of the borehole during injection or extraction of constant heating power. Major influencing factor on the quality of such a test is the accuracy of temperature and heating power measurement which is determined by the quality of sensors and monitoring equipment. Additionally, the evaluation method of data and the accuracy of the mathematical model of the BHE are of significant importance. In 2001 an experimental apparatus similar to those developed in USA and Sweden was put in operation by ZAE-Bayern in Germany and a total of around 15-20 Thermal Response Tests are performed per year. From the operational experiences gathered, the apparatus was improved over the years by implementing highly-accurate temperature sensors and flow-meters and in 2004 a novel control-technique was integrated for imposing a constant heating-power to the borehole. The present paper gives a description of the experimental setup, the error analysis of the equipment, summarize the experiences gained from the numerous field measurements carried out and define quality requirements for the Thermal Response Test.

GEOTHERMAL RESPONSE TESTS USING CONTROLLED MULTI-POWER LEVEL HEATING AND COOLING PULSES (MPL-HCP): QUANTIFYING GROUND WATER EFFECTS ON HEAT TRANSPORT AROUND A BOREHOLE HEAT EXCHANGER.

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Classical Geothermal Response Testing depends on applying a constant energy forcing to a Borehole Heat Exchanger and analysing the temperature response in terms of ground thermal conductivity and borehole resistance using the line source or similar analytical approach. In the test the only heat transport mechanism accounted for is conduction, and the principle aim of the test is to measure accurately the ground thermal conductivity.

Although the test is very useful in practice, there are several drawbacks. First of all, only the conductivity and borehole resistance can be estimated. Other parameters (borehole geometry, heat capacity etc) remain unknown. Secondly, to achieve high accuracy in a limited amount of time, a good idea of the thermal response of the ground is needed beforehand. If this information is not available, the test may saturate too quickly (too large energy forcing) or the thermal forcing may be too small, leading to an insufficient temperature response. In both cases the required accuracy of the test is not achieved. Thirdly, ground water effects are not considered. However, ground water flow affects and even may invalidate the test results, as has been shown in experiments performed by us where ground water flow conditions could be controlled.

We recently developed a new test protocol that is based on the idea of using a numerical model and parameter estimation procedure to obtain estimates of any parameter of interest. In this test protocol the thermal pulse is modulated to achieve different energy levels. Pulses of about 24 – 40 hours are used, and both heating and cooling pulses are combined. The analysis procedure can be carried out by basically any

model capable of calculating the energy transfer between a Borehole Heat Exchanger and the Ground. In this case we employ a model based on TRNSYS with DST and/or SBM, which were specifically adapted for this purpose.
To develop the data analysis procedure we carried out a reference experiment, where ground water flow is virtually absent, and in exactly the same conditions an experiment where ground water flow was forced. In this paper we will present the results of this experiment and develop the methodology to quantify ground water effects using a Type III MPL-HCP geothermal response test.

BOREHOLE SEALING IN A COAXIAL HEAT EXCHANGER BY BENTONITE TREATMENT

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To store cold only for direct cooling using Borehole Thermal Energy Storage technology requires more efficient Borehole Heat Exchangers (BHE) than the single or double U-pipes that are normally applied in these types of storage systems. A more cost effective (low thermal resistance) coaxial (concentric) borehole heat exchanger suitable for cooling without chiller machines has been tested in Halifax, Nova Scotia, Canada. Field tests were conducted to determine whether a borehole could be sealed with bentonite to make it water tight and suitable for coaxial type borehole heat exchanger i.e. no groundwater flux. The experiment is part of pre investigations needed for a full-scale pilot BTES cooling plant expected to be realised by the Department of National Defence, dockyard naval base on Halifax Harbour.

Thursday 2:15-3:55
Session 10B
Water and Ice Storage

SNOW COOLING IN SWEDEN

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This paper is based on theoretical studies, measurements, and experience from a snow cooling plant in Sundsvall, Sweden, that has been in operation since 2000. The design, operation and prerequisites for a new Swedish open pond snow cooling plant were discussed. It was found that new snow cooling plants would be constructed in a more compact shape, i.e. deeper, to reduce the natural melt and facilitate operation. Water should still be used as cold carrier, between the storage and the cold load. The recirculation of water has caused problems at the Sundsvall plant and it is suggested that the return water should be sprayed over the storage or located at the bottom of the pond. The in and outlets must be placed to avoid water short cuts in the storage, to enable low temperatures and avoid uneven snow melt. Different methods to produce frozen water, different thermal insulations, the importance of a water-tight pond and boundary conditions, including economy, for snow cooling in Sweden were also covered.

CHILLED-WATER SYSTEM UPGRADES
PRINCETON'S THERMAL STORAGE AND SYSTEM WIDE IMPROVEMENTS

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Chilled water system limitations are a common challenge for many facilities, especially campus configurations (higher education, manufacturing, airports, etc.). Princeton University has successfully operated a district cooling system for more than 40 years. When faced with a major increase in campus cooling demand, Princeton took the opportunity to study and improve many areas of the system that would not meet today's design standards. Some limitations were discovered that involved reduced cooling (tonnage) and distribution (flow) capacity, fluctuating supply temperature and low return temperature – challenges familiar to many district cooling system operators. These technical limitations, which can result in suboptimal economic operation, are typically overcome by adding pumps and chillers; this may not be the most cost-effective solution to install or to operate, however.

Since 2000, when Princeton began planning how to provide significant additional cooling capacity due to a major increase in climate-controlled area, it has taken a broad, campus wide approach to resolving system deficiencies and improving operational flexibility. At its central plant and distribution network, and with local building improvements, it is taking proactive steps to overcome capacity, flow, and temperature limitations and optimize economic dispatch of equipment**.** Typically, efforts to deal with chilled-water limitations are undertaken in isolation, which can reduce the overall value of each individual change. By studying overall system impact, Princeton is able to maximize the cost-effectiveness of each change.

METHODOLOGIES OF ON-GOING COMMISSIONING FOR AN EXISTING BUILDING WITH VRV ICE THERMAL STORAGE SYSTEMS

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This study was aimed for an establishment of methodologies to apply on-going commissioning for variable refrigerant volume (VRV) systems with ice thermal storage tanks in existing buildings. Measurements in an existing building, equipped with VRV ice thermal storage systems, were conducted and the results were evaluated.

A VRV system is a system has several indoor units or evaporators in one condensing unit. In addition, some systems with ices storage tanks use stored ice for sub cooling of the refrigerant to increases the cooling capacity. As a result, they can decrease the compressor energy consumption during daytime, and therefore peak shaving of energy is achieved. However, commissioning of these VRV system are hardly completed, because information such as, control strategies, refrigerant flow rate, not opened to users.

Measurements were conducted in systems for lecture rooms on the second floor and seminar rooms on the fourth floor in the Chubu University Building No. 10. While the lecture rooms on the second floor were regularly used, the seminar rooms on the fourth floor were irregularly used. Items of the measurement were temperature and humidity of each room, electric consumptions of each system, the outdoor air temperature and humidity, and solar insolation.

In this study, we propose four methods to analyze the performance of VRV ice thermal storage systems. The data analyzing methods of temperature and humidity of each room and electric consumptions of each system were investigated using a visualization tool. For understanding the situation of the thermal storage

operation in summer, the ratio of shifted power consumption was calculated. For the amount of the ice loss in the ice storage tank that existed in the operation phase was estimated, it was calculated the ratio of the power consumption at nighttime of the day of no air-conditioning at daytime. To evaluate system performance, the primary energy consumption par total floor area was calculated as an index.

DISTRIBUTED HIGH CAPACITY COLD STORAGE IN DISTRICT COOLING SYSTEMS

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The demand for comfort cooling is increasing around the world. At present, air-conditioning is consuming large amounts of electricity, often during hours of peak power demand. Also, a major part of the electricity around the world is produced from fossil fuels, causing emissions of CO_2 in the atmosphere. To achieve sustainable cooling, thermal storage is likely to play an important role for energy effective and environmentally sound systems. Phase change materials (PCM) have lately raised considerable attention for such storages, since they can be designed to melt and freeze at a selected temperature. Also, their promising ability to reduce the size of storage systems compared to a sensible heat storage system (e.g. water storage) is of importance. In this paper, the district cooling network in Stockholm has been considered. Here, the demand for cooling has increased quickly since the network was introduced in 1995. However, supply is limited and bringing on new district cooling customers will in the future require an expanded cooling capacity in the network. One option is to use small-scale PCM cool storages to be placed at the district cooling customers. Here, the economical feasibility of such PCM cooling storages has been studied, and the results are compared to those of a stratified cold water storage. Results show that there is economic potential for such storages in the district cooling system. Furthermore, the study shows that PCM storage has a lower investment cost than cold water storage. The most critical factor determining the attractiveness of an investment in a small-scale cool storage is each customer's cooling need as represented by its load profile. From a cost-breakdown analysis of a PCM storage system, it is clear that the main cost of the system is not the PCM material but other things like the tank, the controls system, etc. Thus, effective system design with integration of components is very important in addition to finding cheap, reliable and environmentally friendly PCM materials.

Thursday 4:20-6:00
Session 11A
UTES- SCW and Foundation HX

MODELING OF STANDING COLUMN WELLS IN GROUND SOURCE HEAT PUMP SYSTEMS

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The need for alternative low-cost energy sources has given rise to the development of ground source heat pump systems for residential and commercial heating and cooling applications. Standing column wells can be used as highly efficient ground heat exchangers in ground source heat pump systems, where hydrological and geological conditions are suitable. A detailed two-dimensional finite volume model and a simplified one-dimensional finite difference model are introduced in this paper. Both models have been validated against experimental data. Application of the simplified model, which has been integrated into an hourly building energy simulation program, is demonstrated with a brief comparison of systems for a Boston office building. Results show that standing column well systems require less borehole depth

compared to single U-tube closed loop systems. A comparative life cycle cost analysis is conducted considering 20-year system operation.

STUDY OF GEOTHERMAL SEASONAL COOLING STORAGE SYSTEM WITH ENERGY PILES

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This paper describes a study of geothermal system with energy piles that has recently been built in China. This system stores the cooling energy in the cold winter, which can then be used to provide sensible cooling in the hot summer. With a proper system design, the need for an electric water chiller is completely eliminated. In order to assess the potential of application for this system in the sub-tropical region, computer simulations are carried out to obtain the predicted system performance. Both the results of the simulation and the actual operating data of the system indicate that the geothermal seasonal storage system is not capable of meeting the sensible cooling load of the building without relying on an auxiliary chiller. Further simulations are conducted to evaluate the performance of the geothermal heat pump system, which combines energy piles together with a heat pump. The analysis shows that this system can cater for both the sensible and the latent cooling loads. A comparison between the conventional borehole geothermal heat pump system and the energy piles geothermal heat pump system is made with respect to storage capacity, initial cost and energy consumption.

DEVELOPMENT OF A GROUND SOURCE HEAT PUMP SYSTEM WITH GROUND HEAT EXCHANGER UTILIZING THE CAST-IN-PLACE CONCRETE PILE FOUNDATIONS OF BUILDINGS

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Ground-source (Geothermal) heat pump (GSHP) systems can achieve a higher coefficient of performance than conventional air-source heat pump (ASHP) systems. However, GSHP systems are not widespread in Japan because of their expensive boring costs. The authors have developed a GSHP system that employs the cast-in-place concrete pile foundations of a building as heat exchangers in order to reduce the initial boring cost. In this system, eight Utubes are arranged around the surface of a cast-in-place concrete pile foundation. The heat exchange capability of this system, subterranean temperature changes and heat pump performance were investigated in a full-scale experiment. As a result, the average values for heat rejection were 186~201 W/m (per pile, 25 W/m per pair of tubes) while cooling. The average COP of this system was 4.89 while cooling; rendering this system about 1.7 times more effective in energy saving terms than the more typical ASHP systems. The initial cost of construction per unit for heat extraction and rejection is ¥30/W (approx. US$0.30/W) for this system, whereas it is ¥300/W (US$3/W) for existing standard borehole systems. Therefore, this system is expected to be commercially viable.

THERMAL ENERGY STORAGE IN OFFICE BUILDINGS FOUNDATIONS

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Since late nineties office buildings in Germany are being constructed using the surrounding ground of their foundations for heat exchange and seasonal thermal energy storage. The R&D-project “Thermal Energy Storage in Office Buildings Foundations” supported by the Federal Department of Economics and Technology takes a closer look at day to day performance of energy-piles, foundations absorbers and borehole heat exchangers used for heat and cold supply of low energy office buildings. Ten office buildings

(3.500 m² to 73.500m²) are being evaluated regarding dimensioning, implementation and building costs. Five of them are monitored closely to examine and optimize their controls and energy performance.
First results show that it is possible to fit UTES-systems in today's office buildings energy concepts. They are ideal to be combined with low temperature heating or high temperature cooling systems like concrete core activation or heating/cooling ceilings. In this combination UTES coupled heat pumps reach high SPF's. In order to implement a cost-effective seasonal UTES-system, it must be taken in consideration throughout the entire design of a building, that high temperature cooling systems (fluid temp. = 17 to 22 °C) need modern façade-systems which keep the external load out of the offices.
The investment cost per meter energy-pile lies around 17 to 28 €/m. A borehole heat exchanger (BHE) costs about 45 to 75 €/m in Germany. One of the biggest parts of investment costs of the UTES are the heat pumps (30 to 40 %).
In some buildings a lack operation experience led to long lasting underperformance of the UTES-system. Here an undesired overheating of a UTES led to cooling underperformance over years.
The monitoring results that a seasonal UTES performs the best if it is strictly operated during cooling and heating periods only.
Finally operation of energy-pile, foundation absorbers and BHE seasonal UTES is still in the need of optimization as well as research work to reach full user acceptance and better cost effectiveness.

Thursday 4:20-6:00
Session 11B
Ice Storage and Modeling of TES

ECONOMIC, ENERGETIC AND EXERGETIC STUDY OF A WATER TANK INCLUDING PCM MODULES INSIDE

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The Research Group in Applied Energy (GREA) started a research work on Phase Change Materials (PCMs) in 1999. Since then we have been working on different aspects of these materials and have carried out a substantial amount of experiments (thickening, corrosion, heat transfer enhancement) in the laboratory with various types of phase change materials: paraffins, salt hydrates and even fatty acids. Selecting the most suitable PCM for the corresponding application is a crucial point for the good performance of the application.

A promising research line with PCM in GREA is the inclusion of PCM modules in the upper part of a water storage tank in order to increase its thermal capacity without breaking the beneficial thermal stratification, and reduce the required tank volume. First results with a small commercial water tank with and without PCM showed a good agreement between the expected theoretical energy improvements and experimental results for various charging and discharging cases. A local manufacturer of water tanks is partially supporting this research as they foresee a potential new product line of water tanks with PCM inside that have a reduced volume and are able to provide the same thermal performance as the standard water tanks.

This work presents energy and exergy analyses for this new water tank with PCM. The standard water tank is included as a reference case for comparison purposes. A feasibility study is also developed to evaluate the economic savings of a smaller PCM-water tank with the same thermal energy capacity as the larger reference water tank. The effect of various key parameters on the tank manufacturing cost savings is assessed. These parameters include the PCM cost, the stainless steel cost, the tank thermal isolation cost, and the tank volume.

DETERMINATION OF THE HEAT STORAGE CAPACITY OF PCM AND PCM-OBJECTS AS A FUNCTION OF TEMPERATURE

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Phase change materials (PCM) are thermal storage materials with a high storage density for small temperature range applications. One such application is the storage of natural cold of the night to use during daytime, called “free cooling”. Very high energy efficiency can be reached as the cold has not to be generated. Operating the system in a small temperature interval, the accurate determination of the PCM's heat storage capability as a function of temperature and the release of heat from PCM-objects to a heat transfer fluid is crucial. In this paper we report on our work to improve useful measurement methods. The standard measurement method to determine the heat storage capability of a material as a function of temperature is differential scanning calorimetry (DSC) with a constant heating or cooling rate. However, measuring PCM using DSC has to be done very carefully. One problem is the distortion of the signal that arises because of the phase change of the PCM. Our investigations show that this problem can be solved by a modification of the temperature program. A second problem using DSC is that the typical sample size is too small to represent inhomogeneous materials, which is the case for many PCM that contain gelling materials or other additives. Last but not least, subcooling often depends strongly on the sample size and is worse in DSC compared to a real installation. We therefore focused on an improvement of the T-history method which allows bigger samples to be used. Concerning encapsulated PCM (PCM-objects) as used in a real installation, we built another installation to measure heat storage, heat release and power output experimentally. In order to test the accuracy of the different methods, measurements were performed on samples of two PCM and the results compared. The agreement was very good.

EXTENSION OF A TRNSYS MODEL FOR LATENT HEAT STORAGE WITH PHASE CHANGE MATERIALS USED IN SOLAR WATER TANK

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This paper describes the numeric model developed in the framework of the IEA Task 32 to simulate phase change materials (PCM) in water tank storage. This model, based on the enthalpy approach, takes into account the conduction and the convection into PCM as well as into the interface between PCM and water of the storage. It has been implemented in an existing TRNSYS model of water tank storage and allows the simulation of a storage tank filled with water and PCM modules of different shape such as cylinders, plates or spheres bed. Comparisons between measures and simulations show the good potential of this model.

VALIDATION OF A TRNSYS SIMULATION MODEL FOR PCM ENERGY STORAGES AND PCM WALL CONSTRUCTION ELEMENTS

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The idea to use phase change materials (PCM) for energy storage is to make use of the latent heat of a phase change, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for temperature stabilization and for storing heat with large energy densities in combination with rather small temperature changes. The application of PCMs in wall layers, such as plasters or gypsum boards, or in the ceiling construction adds thermal mass to the building, thereby avoiding unpleasant temperature variations of the inside room temperature, or leading to a considerable reduction of room temperature peaks during summer.

In the current paper we present a simulation model for a PCM storage tank integrated into the simulation environment Trnsys16. The model is capable of treating both micro-encapsulated PCMs (so called PCM-

slurries) as well as modules of PCM materials of various shapes (cylinders, spheres, plates) immersed into a water storage tank. The model results are validated against measurement data showing excellent agreement between simulation results and experiment.

In addition, we present a PCM wall model for Trnsys16 that can be coupled to the multi-zone building type 56 of Trnsys16. The model is applied to a building having a wall construction consisting of a PCM plaster (micro-encapsulated paraffins with a melting range between 23°C and 26°C) at the inside wall surface. The comparison of the simulation results with those from a reference building with conventional plaster material clearly shows that the PCM plaster reduces the overheating problem during a summer period as long as the room temperature do not exceed the phase change temperature of the micro-encapsulated paraffins.

Friday 8:30-10:10
Session 12A
Geothermal Systems

CANADA'S LARGEST BTES SYSTEM: 74,000 M BOREHOLE FIELD

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The first large-scale BTES system in Canada was installed at the University of Ontario Institute of Technology (UOIT), Oshawa, Ontario in 2003. The UOIT first opened its doors to students in September, 2004. At full build-out, there will be eight campus buildings constructed around a landscaped courtyard. A central plant provides heating and cooling for the entire campus and each building incorporates energy efficient architecture and equipment. The university's curriculum includes research in alternative energy and thermal energy storage.

The ground in the borehole field consists of 44 m of glacial deposits and 156 m of shale and limestone bedrock. There is negligible groundwater flow beneath the campus, making the geology ideal for a BTES system. A thermal response test, based on the Swedish test device (TED) was conducted in a 200 m deep test hole. The Earth Energy Designer (EED) numerical model, developed by researchers in Sweden and Germany, was used to estimate the required number of boreholes in the BTES field.

The summer cooling load for the campus buildings is dominant, with a peak load of 7000 kw. The EED model output specified a total cooling length of approximately 74,000 m. The final BTES design included 370 boreholes, drilled to a depth of 200 m, on a 4.5 m grid. The field was installed in the 0.7 ha central courtyard of the campus. Five 200 m deep monitoring boreholes were also installed.

Drilling of the 375 boreholes was carried out over a record-breaking 105-day period. The drilling was accomplished by three drilling rigs, operating 24 hours per day, 7 days per week. The overburden and shale portion of each borehole was cased with 150 mm diameter steel pipe. The limestone portion of each borehole was drilled with an air-driven down-the-hole hammer.

The use of water-filled boreholes, a common practice in the Scandinavian countries, was utilized because of the non-fractured limestone rock. This allowed much more efficient installation of the U-tubes. The 32 mm diameter polyethylene U-tube piping was delivered to the site on 2000 m reels. A single crew of four installed up to 3000 m of U-tubes per day.

The BTES system was put into operation in September 2004. The BTES field performance has been monitored by strings of temperature transducers in the 5 observation wells. Monitoring of the thermal distribution in the borehole field during the first 18 months of operation will be examined. Experience with

other large BTES indicates that it may take 2 to 3 years of operation before a stable thermal equilibrium is established between the ground and the borehole heat exchangers.

A GROUND SOURCE ENERGY PLANT FOR THE NEW ASSEMBLY FOR WALES

drs A.J. van Gelder[1], dr H.J.L. Witte[1] & P. Heaton[2]
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The new National Assembly for Wales in Cardiff Bay is scheduled for completion in September 2005. This event is not only a political achievement but also a milestone in environmentally friendly building.

Architect Lord Richard Rogers' key in the design formula were sustainability and innovation. The designers accomplished this by using local materials and bringing waste to a minimum. Another feature of this environmentally conscious building style is the natural ventilation and temperature control. The marked funnel on the roof is not only a defining feature of the architecture but also a functional design, as it enhances natural ventilation, rejecting warm air and allowing cooler air to be drawn in. As a source of heat and cool a system of ground source heat pumps is installed, that allow very efficient heating and cooling, making use of the earth beneath the building.

For the New Assembly for Wales building Groenholland developed a new approach of applying ground source heat pump technology. Often, when both heating and cooling are required, the heat pump is reversed, the function of the condenser and evaporator are changed. This means that the building is the "warm side" in winter and the "cold side" in summer. It also means that only heating or cooling is possible at any given time. While very efficient and practical in many situations, it is not possible to cool and heat concurrently. We therefore developed a system that primarily transfers heat from the air conditioning system to the heating system. The ground loops are coupled to the side that requires the lowest load at a given time. For instance, in summer the building will be dominated by cooling and the heat pumps will generate excess heat, the "warm"side of the heat pumps will then be connected to the building and the ground loops. The control software developed by us allows the system to operate completely autonomously, even a connection to the building control system is not needed.

An integrated design approach was followed, where a careful analysis of the interactions between the different components was made. The goal was to design a plant that can provide the full capacity needed, but that is optimized to provide the average capacity at the highest efficiency possible. Several novel approaches were implemented, both on the hardware level and in the control software. The final plant is of high efficiency and of very compact design, allowing significant space-savings as well.

A VERY LARGE DISTRIBUTED GROUND SOURCE HEAT PUMP PROJECT FOR DOMESTIC HEATING: SCHOENMAKERSHOEK, ETTEN-LEUR (THE NETHERLANDS).

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Schoenmakershoek is a new development, of about 1400 houses, located in the southwest Netherlands (province of Brabant) to the north of the municipality of Etten-Leur. An Energy Vision was developed by the municipality from the onset of the project, and heat pumps are an integral part of this "all electric" energy-neutral vision. Etten-Leur has a high ambition level with respect to the use of renewable energy: the long-term policy of Etten-Leur is to achieve energy-neutral building for new developments by 2020. Within the framework of this long-term policy the goal is to attain 40% energy neutral housing projects by 2010.

To successfully realize such a large scale, high density ground source heat pump project, it is paramount to pay special attention to the feasibility, performance, long-term sustainability and installation quality. The conditions for the design and implementation of individual heat pump systems (typically consisting of 50 - 100 units each) within the total plan project needs to be well defined. Therefore, after the preliminary general feasibility study had been carried out, a second phase was entered where especially the feasibility of long-term use of ground source closed loop heat pump technology was evaluated.

Principal questions included how the large number of heat exchangers affect each other within the plan area, if - given the configuration - cold zones would develop and if ground water flow would play any role in heat transport on the location. To address these questions a large scale simulation was carried out using the 2D simulation code HST2D, with a realistic heat exchanger geometry consisting of two submodels of about 1000 heat exchangers each and incorporating heat conduction as well as ground water flow as a heat transport mechanism. Several energy scenarios were evaluated and finally the conditions for sustainable use of the ground for heating were defined using this study. Subsequently three trial boreholes were drilled and ground water observation wells were installed at depth of the two main aquifers to allow ground water measurements. A heat exchanger installed was in two of the boreholes as well. In addition to the detailed soil stratigraphy and depth of aquitards, two In Situ Response Tests yielded high-quality information on the thermal characteristics of the soil. Measurements of ground water gradient led to an accurate assessment of ground water flow on the location.

These technical data now form the backbone for the implementation phase of the project, allowing clearly defined design conditions in terms of minimum temperature levels that must not be exceeded as well as thermal balance that need to be achieved.

COMPARATIVE ENERGY PERFORMANCE BETWEEN A GEOTHERMAL HEAT PUMP SYSTEM AND AN AIR-TO-WATER HEAT PUMP SYSTEM FOR HEATING AND COOLING IN TYPICAL CONDITIONS OF THE EUROPEAN MEDITERRANEAN COAST

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We report the cooling and heating performance of a ground-coupled heat pump system (GCHP) installed at the Universidad Politécnica de Valencia, Valencia, Spain. The framework of this study is the European Project GEOCOOL whose main goal is the development of a ground source heat pump system for cooling and heating, targeted specifically at coastal applications in the South European region. The GCHP heats and cools an academic building with 15 and 22 kW peak load in heating and cooling mode respectively. The ground heat exchanger was designed with six boreholes of fifty metres depth and diferent backfillings in order to analyze the performance with different characteristic Mediterranean soils. The analysis period started in February of 2005 and it lasted throughout one year. In order to compare the performance with a conventional air-conditioning system, GCHP was alternated with a conventional air-water heat pump installed on the building roof. Air-water system has operated each Monday and GCHP from Tuesday to Friday. Power consumption and fluid temperature of both systems were monitored with one minute interval between measurements. The analysis of the huge amount of data showed important differences between both systems. The seasonal performance factor (SPF) of the geothermal system at the end of the seasons was 3,46 and 4,36 in heating and cooling mode respectively whereas it was 2.00 and 2,72 for the air-water heat pump. These results involve an electrical energy saving of about 40 %. Finally, we conclude that the GCHP is a feasible, energy efficient and environmentally friendly system for heating and cooling at applications in the South European region.

Friday 8:30-10:10
Session 12B
Transportation of Energy by Utilization of Thermal Energy Storage Technology – Annex 18

FUNDAMENTAL STUDY ON "THERMAL TRANSPORTATION SYSTEM USING ICE & WATER BY ONE-PIPE LOOP SYSTEM" (THE MAXIMUM ICE PACKING FACTOR FOR TRANSPORTATION OF BLOCK ICE)

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"Thermal transportation system using Ice & Water" have spurred interest in the field of thermal storage since this system hold promise reduction in pipe diameter and lower power consumption needed for transport. In addition, construction costs and running costs are lower than in conventional systems.

In previous studies, we conducted research on one-pipe loop systems for district cooling using block ice. The control of this system is characterized by retaining ice to the end of the district piping, which allows consumers to use cold water kept at zero degrees Celsius. The warmed water returns to the district piping after the consumers have used the cold water. It then undergoes direct heat exchange between the warmed water and the ice, as a result of which the consumers can use only the latent heat of fusion of the block ice. Furthermore, in this system, the district piping is treated as part of the thermal storage tank. A brief summary of the system contains information on pressure loss, measurement of heat quantity, how to inject the ice and the characteristics of direct heat exchange. This report examines the maximum amount of transported heat that is considered to be most important for a high-density heat transport system

THERMAL ENERGY TRANSPORT AND STORAGE WITH MULTI-FUNCTIONAL FLUIDS THE EFFECTIVE THERMAL CONDUCTIVITY

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The technology of transport and storage of thermal energy with recently developed thermal multi-functional fluids (phase change slurries) is shortly addressed. The main focus is directed on the definition, physical modelling, calculation and measurement of the effective thermal conductivities of micro-capsule slurries. The thermal conductivity is a well-defined physical property for a mono-component and mono-phasic substance. If there are more components, e.g. solid particles in a fluid, the overall or effective thermal conductivity becomes a model quantity. It is calculated by a resistivity network in analogy to the calculation methods for electric circuits. Such models have been developed in 1892 by Maxwell, and later by Jeffrey and Philipov, etc. For such slurries the Jeffrey model is generalized and named the *Jeffrey Micro-Capsule Slurry Model*. With a new developed heating pulse method a calibration of measurements of the thermal conductivities with the values of water was successful. In a second step first on-line measurements of the effective thermal conductivities of microcapsule slurry have been performed. The experimental results show a good agreement with the values of the Jeffrey Micro-Capsule Slurry Model.

COST-EFFECTIVENESS OF A HEAT ENERGY DISTRIBUTION SYSTEM BASED ON MOBILE STORAGE UNITS: TWO CASE STUDIES.

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The use of industrial waste heat for energy supply in a remote location is an excellent way to reach better energy efficiency. Mobile energy storage systems transported by truck may bridge the gap between heat source and demand site in cases where a pipeline-bound connection cannot be realized cost-effectively due to a mismatch in distance and demand. For the transportable heat energy storage unit, phase change materials or sorption materials are promising candidates due to their high energy storage capacity. However, the conditions under which such an energy distribution system can be run profitably need to be clarified.

In this paper, we present the results of two feasibility studies carried out for an industrial plant and a waste incineration plant located in Germany. Calculations take into account commercially available latent heat storage modules based on sodium acetate as well as a zeolite sorption system proposed by the authors which can also provide cooling and dehumidification. Variation of storage capacity, system scale, system uptime, distance from heat source to user and user load profile is performed and shows that all factors have significant influence on the economic performance.

Sorption technology proves generally less expensive compared to the phase change approach. However, providing air conditioning turns out to be far off the mark and overall cost-efficiency for heating applications is only obtained for close to optimal conditions. The lowest value for the actual costs of heat energy distribution via mobile storage units evaluated for a real case scenario is 24 €/MWh (i.e. 30 USD/MWh approximately), which is competitive compared to oil. Further optimization may yield a reduction to below 20 €/MWh (24 USD/MWh), thus also beating current prices for natural gas.

APPLICATION OF PHASE CHANGE MATERIALS AND PCM SLURRIES FOR THERMAL ENERGY STORAGE

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The idea to use phase change materials (PCM) for the purpose of storing thermal energy is to make use of the latent heat of a phase change, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for temperature stabilization and for storing heat with large energy densities in combination with rather small temperature changes.

The successful usage of PCMs is on one hand a question of a high energy storage density, but on the other hand it is very important to be able to charge and discharge the energy storage with a thermal power, that is suitable for the desired application. One major drawback of latent thermal energy storage is the low thermal conductivity of the materials used as PCMs, which limits the power that can be extracted from the thermal energy storage.

In the work presented in this paper different ways of the integration of PCMs into a thermal energy storage were investigated. Different PCM materials, with and without enhancement of the thermal conductivity, were used, and their performance concerning the resulting charge/discharge power of a storage tank were tested experimentally.

Friday 10:35-12:35
Session 13A
Aquifer Thermal Energy Storage

TWO-YEAR EXPERIENCE IN THE OPERATION OF AN AQUIFER THERMAL ENERGY STORE BASED ON SURPLUS HEAT ARISING FROM A GAS AND STEAM COGENERATION PLANT AT NEUBRANDENBURG / NE GERMANY

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An aquifer for storage of the waste heat arising from the gas and steam cogeneration plant of the Neubrandenburger Stadtwerke GmbH (public utilities) was installed and comissioned in 2004. The plant is based on the wells and surface installations of a geothermal heating plant which has been operated since 1987 using Hettangian and Upper Postera aquifers at a depth between 1,200 and 1,300 m. After retrofitting, the waste heat arising from the cogeneration plant in summer at a temperature of 80 °C and amounting to approx. 4 MW is stored in the subsoil. In the next winter, this heat will serve to supply the base load of a district heat supply network with a connected load of 12 MW.
This paper describes the plant concept and presents operating data of the first complete annual cycle of heat charging and discharging in 2005 and 2006.
During this period, the store to a high extent came up to the expectations tied up with its technical operation. There were not to be stated any considerable technical problems which could be assigned to the operation of the store. The water chemistry was manageable as well. Solids did not precipitate at any time.
Actually, cuts still have to be made regarding the energetic efficiency of the store operation. Totally, the store was charged with approx. 14,000 MWh, however, only 6,000 MWh were discharged. This is not caused by the store itself which behaves exactly as predicted, but it is due to the characteristics of the connected heat producers and consumers. In particular a still too low potential of the heat sink in winter or the still too high return flow temperatures in the heating networks hinder the sufficient discharging of the store.

MODELLING OF THE CHALK AQUIFER IN CENTRAL LONDON FOR A PROPOSED OPEN COOLING SYSTEM

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As part of the growing interest in aquifer thermal energy storage (ATES) in the United Kingdom a proposal has been made to use the chalk aquifer underlying central London to cool a new building development. The economic case for the system has been made by freeing up valuable floor space that would normally be used for conventional cooling systems. Recent regulations from the Environment Agency in England state that licenses are unlikely to be granted for abstractions greater than 0.2 Ml/day. For an ATES system of any size therefore, the majority of the water abstracted from the central London aquifer will have to be re-injected. As the proposed building does not have a balanced energy demand throughout the year (a net cooling demand) there is a continual injection of heated water into the aquifer. This heated water has the potential to migrate to the abstraction boreholes and affect the long term performance of the system. The key concern for the system design is at what point in time and under what conditions the temperature at the abstraction borehole causes the cooling system to stop functioning effectively. To provide some design guidelines, Arup Geotechnics constructed a number of numerical models to simulate the response of the aquifer to different system configurations.
Results suggest that the proposed system can only function in the long term by reducing the cooling energy demands placed on the aquifer or by considering innovative methods of either adding cold to the aquifer in the winter or removing excess heat. Reducing the value of delta T prolongs the lifespan of the system as do possible bleed flows. At the flow rates needed for the proposed system it is unlikely that the fracture

network in the chalk will have a significant impact on the heat transport. However, the presence of high permeability zones will have a detrimental effect. An accurate prediction of the heat flux through the chalk is difficult without a good knowledge of the flow characteristics. An effective ATES thermal test for the chalk is therefore currently under development.

CLOGGING RATE OF RECHARGE WELLS IN POROUS MEDIA

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Research makes clear (e.g. IEA ANNEX 13) that clogging of recharge wells (ATES and ASR) by suspended solids is common and, despite advances in infiltration well technology, remains a key determining factor of infiltration well performance. The clogging potentials of suspended solids in water is not just a function of concentration, but also of particle size and composition. Since 2000 in the Netherlands the MFI is used to estimate the clogging potential of water that has to be infiltrated using recharge wells. The MFI gives no detailed information about each individual particle, instead it gives a direct value of the clogging potential of the water. In 200 a quantitative relation between clogging rate and MFI was developed. The relation has a theoretical-empirical base and was derived by using published data of experiments performed by Olsthoorn (1982) and Pyne (1994). In the years between 200 and 005 the relation has was used to design over 250 ATES-systems. During these years the relation has proven itself as reliable and as a useful tool to predict clogging rates of recharge wells, especially considering the uncertainties in measured parameters like MFI and permeability. Further an easy, cheap (fast) and reliable apparatus was developed.

SOIL-WATER PIT HEAT STORE WITH DIRECT CHARGING SYSTEM

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At the Institute of Thermodynamics and Thermal Engineering field tests on different concepts and designs of pit heat stores are carried out in the frame of the research project “Further Development of the Pit Heat Storage Technology”. One main emphasis is the development of an efficient and cost-effective pit heat store for seasonal heat storage, particularly in combination with solar assisted district heating systems.
A promising concept is a soil-water pit heat store with a direct charging system. The heat store is filled with the excavated soil (or sand) after the installation of the insulation and the liner thus saving the money for the gravel and the landfill. Traditionally soil-water pit heat stores have been built with plastic piping as heat exchanger for indirect charging (similar to a floor heating system).
In the case of the new concept the water is circulating through horizontal and vertical gravel channels in order to save the complicated and costly piping. The sand/soil packages are packed in geotextile (fleece) in order to prevent elutriation. The dominating heat transfer mechanism from the fluid to the saturated soil packages is heat conduction as convection through the sand/soil packages can be neglected..
The research soil/water pit heat store consists of a 200 m³ pit using 0.1 m thick gravel layers and three packages of fine sand (instead of soil) with a height of 0.6 m. For charging and discharging perforated PP pipes (DN150) are placed in the top and bottom gravel layer, respectively. Flow rate, supply and return flow temperatures as well as various soil and gravel temperatures are monitored in order to determine the heat being transferred from the gravel layer to the soil. The measured results are compared with numerical results obtained by CFD simulations. The CFD simulation results, which agree with the measurement data, indicate that the concept is technically feasible. The proof of economic benefit in comparison to a gravel-water pit heat store is object to further work.

Friday 10:35-12:35
Session 13B
Thermochemical TES

THERMO-CHEMICAL STORAGE FOR SOLAR SPACE HEATING IN A SINGLE-FAMILY HOUSE

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The development of an efficient and cost-effective heat storage is still one of the major technical challenges for the widespread use of solar thermal energy for space heating. Sorption heat stores are a promising approach to reach high solar fractions with relatively small storage volumes. A new compact design of a closed-cycle sorption storage system using silica gel and water as working pair has been developed and tested in the laboratory. The new design includes all major components (adsorber, evaporator/condenser) in a single container. The new compact system design for a sorption storage system has shown an improved operation of the sorption principle. Pressure and heat losses within the system could be reduced significantly.

However, the most critical point remains the available temperature lift during adsorption. The sorption heat storage principle has a number of disadvantages compared to a standard solar combisystem using a water-filled storage tank. These disadvantages lead to the conclusion that a sorption storage system cannot efficiently be used for short-term storage. The advantage of storage without thermal losses (separation of adsorbent and working fluid) can only make an impact if it is used for longer-term storage. At the same time the material pair has to deliver a sufficient temperature lift that compensates the disadvantages.

The available temperature lift of silica gel and water as working pair is only sufficient with water contents of approximately 2 – 12 %. This is significantly less than the total adsorption potential of 35 kg water per 100 kg of silica gel. That means that the energy density that can be reached with this material is much lower than previously thought and much larger storage volumes would be necessary. Materials with improved characteristics are available but are not ready for market introduction for this type of application (cost, corrosiveness etc.). Therefore, it will be the task of future projects to find a material combination that fulfill the requirements of sorption systems for storage purposes.

OPTIMIZATION OF THERMOCHEMICAL STORAGE BY DEALUMINATION OF ZEOLITIC STORAGE MATERIALS

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Thermochemical storage of heat can contribute to environmental benefits by utilization of waste heat as well as solar heat for space heating and cooling applications. One of the main attractions of this technology is the loss free long term storage of thermal energy for heating, cooling and drying of buildings. For all of this applications, however, the temperature level of the heat source available for charging of the storage influences the choice of the porous material. Till now ordinary zeolites for higher charging temperatures (>450 K) and silica gel (<370 K) were the most common products for thermochemical storage applications. Recently developed storage materials based on microporous silicoaluminophosphates are closing the gap between zeolites and silica gel. The disadvantage of those materials is their synthesis method including an organic template as structure directing agents which has to be removed from the porous structure after the synthesis (by oxidation in most cases). Therefore, we were in search of another solution of tailoring zeolitic storage materials for low temperature applications. A partial dealumination of the zeolite Y for instance by a hydrothermal treatment reduces the number of Al atoms and cations in the zeolite without changing the crystal structure. A reduced cation concentration in the zeolite leads to a lower electrostatic field in the micropores, diminishes the adsorption strength of the water and, hence, lower the desorption temperature (corresponds with the charging temperature of the storage). We used thermogravimetry, differential

scanning calorimetry, the measurements of water isotherms as well as a lab-scaled storage of 1.5 L volume to investigate the adsorption, desorption and storage properties of a set of faujasite type zeolites with increasing lattice silicon to aluminum ratio between 1 and 30. The optimum ratio amounts to 5-10 with respect to a charging temperature of <420 K and a specific energy storage >150 Wh/kg.

THERMOCHEMICAL STORAGE FOR AIR-CONDITIONING USING OPEN CYCLE LIQUID DESICCANT TECHNOLOGY

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Liquid desiccant cooling systems (LDCS) are a first class option for the use of waste heat in air conditioning processes. LDCS dehumidify air by means of an aqueous salt solution, such as a Lithiumchloride solution, and cool it subsequently in direct or indirect evaporative coolers. The salt solution is diluted while drying the air and has to be regenerated at temperatures of 60 °C to 80 °C. If concentrated and diluted solutions are stored separately, energy for dehumidification can be stored thermochemically for some time or can be transported over some distance. However a cooled dehumidifier and a low flow technique are required to achieve a high energy storage density, making energy storage economically attractive.

The Bavarian Center for Applied Energy Research, ZAE Bayern, has developed a cooled low flow desiccant dehumidification technology within the recent years and documented its high energy storage potential. L-DCS Technology GmbH, Ismaning, Germany, has set out to make this technology commercially available. A development and demonstration project started in 2001 aimed at the following objectives: developing and testing of system components such as absorber, regenerator, indirect evaporative cooler and storage equipment, demonstration of the present state of liquid desiccant storage technology and cooling of a Munich jazz club.

The system components have been designed, manufactured and their performance has been tested. The jazz club can be cooled. The cooling system, equipped with extensive measurement instrumentation, has proved to be an excellent facility for performance tests of absorber and indirect evaporative cooler. The performance of the indirect evaporative cooler and the fan coil units in the jazz club is close to what has been expected. In the first tests, the absorber-regenerator-unit did not yet achieve the intended performance in dehumidification and energy storage capacity, the authors, however, are confident to lift the performance to an acceptable level.

THERMAL STORAGE WITH THE THERMO-CHEMICAL ACCUMULATOR

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The Thermo-Chemical Accumulator is a closed system absorption heat pump process with integral heat storage in the form of crystal salt. The technology is being currently developed in the batch mode so that a unit is either charging or discharging, with a switching unit consisting of three-way valves to switch external circuits to the two units. The salt lithium chloride is used at present as this has properties that suit the process in terms of crystallisation temperatures. The main difficulties with the technology, apart from the standard problems of vacuum systems, are those of unwanted crystallisation and of corrosion. The process induces crystallisation, but this has to be contained in such a way so that pumps and tubes are not blocked. The initial problems with unwanted crystallisation, corrosion and vacuum leakage have been solved. The process has undergone rapid development over the last few years and is now being

commercialised. The main targeted market niches are solar cooling/heating, polygeneration and distributed cooling with district heating as heat source.

This paper describes the results of lab measurements and field trials, as well as modelling and simulation studies for the production prototype machine ClimateWell 10. The results show that the process is now reliable and that significant storage is possible and indeed useful in a system context. The tested machine comprises two identical units that each has a storage capacity of 25 kWh cold and 35 kWh heat and maximum cooling/heating capacities of 10/18 kW. All these capacities are shown to be dependent on the boundary conditions and also the state of charge. Charging temperatures increase or charging rate decreases with increasing state of charge. Similarly the chilled water supply temperature increases or cooling rate decreases as the state of charge decreases. Cases where the thermal storage has been shown to be of benefit are described and discussed. In certain cases it is optimal to use the two units in parallel, both charging/discharging simultaneously, while in others the alternating batch mode is preferable. The thermal COP of the machine is approximately 65% for cooling applications and 90% for heating, although this is dependent on operating conditions and the applied control strategy.

PACKED BED REACTOR DEMONSTRATION OF MAGNESIUM OXIDE/WATER CHEMICAL HEAT PUMP

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A chemical heat pump that uses a reversible magnesium oxide/water reaction system was discussed to promote efficient thermal energy storage and utilisation. The possibility of the chemical heat pump was examined experimentally using a laboratory-scale heat pump packed 7.0 kg of reactant and having 500 W class output.

This heat pump enables thermal energy to be stored via the dehydration of magnesium hydroxide and releases the stored energy on demand via the hydration of magnesium oxide. An experimental study of the heat pump was discussed using the laboratory-scale heat pump on the standpoint of the thermal performance demonstration of the heat pump. Cylindrical bed type reactor was installed in the heat pump. A developed reactant pellet of magnesium hydroxide was packed in the reactor as a precursor. Temporal changes of reaction conversion and bed temperature distribution were measured during operations. A heating tube installed in the bed was used for the heat output recovery at the hydration operation. The heat pump operation cycle of hydration and dehydration were repeated under a variety of operating conditions. The heat pump performance and reactant durability was demonstrated from the operation. Thermal energy storage density over 1 MW/kg under 85^{o}C output was evaluated from the experiment. Two-dimensional unsteady numerical analysis of the packed bed reactor was examined to understand the experimental result of the heat pump. Heat and mass transfer phenomena in the bed reactor were discussed to enhance the performance of the heat pump.

Friday 2:15-3:55
Session 14A
UTES- General

FEASIBILITY STUDY OF SNOW MELTING SYSTEM USING GROUND THERMAL ENERGY IN JAPAN

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A half of the Japanese land has been legislated as the heavy snowfall area by the government and more than twenty million people live there. In order to enhance urban appeal as well as the safety and comfort daily life, the snow melting system of the pavement has been getting more recognition in the central are of the city. From energy conversation and CO_2 reduction as well as saving running expense point of view, snow melting system using ground heat source heat pump as heating unit has been recognized as the most promising potential.
In this paper, the outline of the developed novel designing and performance prediction tool is explained first. Next, a new type heat pump with an inverter-control compressor and measurement of its performance are explained. Last, possibility region for direct circulating for snow melting system is discussed by using developed designing tool and the effect of grid spacing of GSHP-SM with heat recharge applied collected solar energy through embedded piping in the pavement during summer is also discussed.

NEW STEPS IN SEASONAL THERMAL ENERGY STORAGE IN GERMANY

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Seasonal thermal energy storage is under investigation in Germany since the beginning of the 1980's. In the context of the R&D-program Solarthermie-2000 eight demonstration plants for solar assisted district heating with seasonal thermal energy storage were built from 1995 to 2002. The comprehensive monitoring data and experiences show that all investigated storage concepts are working without major technical problems.
In 2006 two new R&D-plants are realized with support from the German federal energy research program Solarthermie2000plus. The storages are integrated in central solar heating plants, storing solar thermal energy during summer to provide a district heating net with solar energy also through the heating period in winter. The designed solar fractions of the new plants amount to 50 % of the total annual heat demand for space heating and domestic hot water preparation. Each plant comprises an advanced or new storage technology. In Munich a hot-water tank with a water volume of 5,700 m³ will be built of prefabricated concrete elements. Together with a newly developed heat insulation system and a stratification device the construction cost is expected to be quite a step lower compared to formerly built concrete tank storages. In Crailsheim a borehole thermal energy store with a ground volume of 37,500 m³ will be built. The integration of the thermal insulation system into the storage takes care of the groundwater flow in the upper storage levels.
Ongoing R&D will focus on improving the cost-effectiveness of the storage technologies by a further reduction of the specific storage construction costs and by increased annual heat output of the storage. More cost effective storage technologies are considered for the implementation in different applications like solar and biomass systems.

USING SOLAR ENERGY TO MAXIMIZE THE EFFICIENCY OF GEOTHERMAL HEAT PUMPS

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Energy efficiency changes to the existing residence were started back in 1993, the first being a 200 square foot hot air panel. Since that time progressive solar changes have be ongoing including liquid collectors, water storage and a new oil fired heater all integrated together. Energy savings have been dramatic. The typical yearly oil bill for DHW and heating, pre oil price spikes, was around $200.00. (Now about $300.00). To complete the major energy goals of the structure from a heating and cooling perspective, the oil fired water heater is being replaced with a horizontal ground loop geothermal system along with increases in solar water storage and gross collector area. The larger storage will be in series, selectively, with the ground loop during heating season, driving the EWT for the heat pumps at their allowable maximum for a large percentage of the time. Direct solar ground heating of the trench is being experimented with as well, in what could be considered a worst case scenario heat retention model.

This project is a work in progress and may see heat pump installation by the time of the conference.

GROUND-SOURCE HEATING AND COOLING - A SIGNIFICANT CONTRIBUTE TO CO2 REDUCTION IN SWEDEN

OlofANDERSSON

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In Sweden, ground source energy systems, with a number of different configurations, have been used for approximately 40 years. The most common ones are ground coupled heat pumps for energy extraction from vertical boreholes (“rock heat”) and horizontal coils in the upper soil (“topsoil heat”). Currently there are some 300 000 of these systems in operation. Also groundwater is commonly used for extraction of heat (“groundwater heat”) or cold (“groundwater cold”). In general, the energy from the underground is regarded as a renewable source of energy, and contributes currently with some 10 % of the total space heating in the country. Since these systems preferably replace burning of fossils, they represent a significant reduction of CO2 emission in the country.

In the later two decades, a new generation of systems has been developed and implemented on the market. These systems, underground thermal energy storage (UTES), combine heating and cooling and are preferably used for commercial buildings and institutions. Some large-scale applications can also be found connected to district heating and cooling systems. There are two such concepts that have successfully been implemented on the Swedish energy market, aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES). The number of ATES has steadily grown to some 50 large-scale plants at the end of 2005, while BTES applications show an exponential growth. The estimated number of plants is currently the order of 300. The sources of energy that are stored is normally a mixture of natural heat or cold and waste energy, especially waste cold from heat pump evaporators. The cold production from these systems replaces electricity, while the heat production replace fossil fuels.

In this paper statistic estimates on applications of different systems, factors impacting the market penetration are given, as well as calculations on the reduction of CO2. Furthermore, the conditions for the future use of these systems are addressed.

Friday 2:15-3:55
Session 14B
PCM in Buildings

MICROENCAPSULATED PHASE CHANGE MATERIALS (PCM) FOR BUILDINGS APPLICATIONS

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Phase Change Materials (PCMs) have been considered for thermal storage in buildings since before 1980. With the advent of PCM implemented in gypsum board, plaster, concrete or other wall covering materials, thermal storage can be part of the building structure even for light weight buildings.
This study investigates the inclusion of PCM in concrete. An innovative concrete with PCM was developed using a commercial microencapsulated PCM, with a melting point of 26ºC and a phase change enthalpy of 110kJ/kg. Mechanical strength tests of this new concrete showed lower compressive and flexural strength values than normal concrete, but they still fulfils requirements for non-structural and structural walls. In the latter case, though, they are not recommended as the values are to close to the current lower limits. Further improvements to increase the mechanical properties of this new concrete with PCM are expected.
This novel concrete was used in the construction of a small house-sized cubicle that was fully instrumented to monitor and evaluate the thermal characteristics. A second cubicle with the exact same characteristics and orientation, but built with standard concrete, was located next to the first one as the reference case. In this way conventional elements and the new developments are being tested simultaneously.
During summer and autumn 2005, the behaviour of such cubicles was tested. The results were very good, since temperature differences up to 3ºC were observed between the conventional concrete cubicle and the PCM concrete cubicle and peak temperatures in the PCM cubicle were shifted to later hours. Different situations were tested, namely the effect of opening windows all day, and the effect of opening windows only at night, as a free cooling system. A Trombe wall was added to the south façade; because the effect of the PCM would be used all year long in Mediterranean weathers to reduce both cooling and heating demands.

ENERGY EFFICIENT THERMAL ENERGY STORAGE FOR DX AIR CONDITIONING

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The growing demand for peak electrical power and increasingly congested electrical transmission lines is the primary driver of excessive/marginal emissions caused by peak electrical energy generation. Thermal energy storage systems are now available for direct expansion air conditioning that not only shift peak energy but are also energy efficient.

This presentation addresses:

- Energy efficient Thermal Energy Storage (TES) for DX air conditioning systems
- Peak energy use and its impact on power plant emissions

TES for DX Systems
The root cause of the on-peak electrical problem is the growing demand for air-conditioned comfort. On a typical summer day, one third or more of all the energy transmitted on the domestic grid is consumed by either residential or commercial air conditioners. There is a growing awareness and sensitivity of the economic and environmental impact associated with the demand and supply of summertime peak electricity.
Thermal & Distributed Energy Storage solves the problems of increasing on-peak demand and increasing grid congestion without a loss of user cooling comfort. Thermal Energy Storage has been commonly used

for chilled water based central systems. Ice Energy has introduced a transformational technology efficiently bringing the peak reduction advantages of thermal energy storage to refrigerant based direct expansion air conditioning systems. This presentation will explain the operations of the system and its integration with conventional DX systems.

RADIANT HEATING AND COOLING SYSTEMS: AN ALTERNATIVE APPROACH TO PROVIDE LOW COST ENERGY EFFICIENT BUILDINGS

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For the building mechanical system, a “thermo-active slab” system should be considered. Radiant heating and cooling from the overhead concrete floor slab performs the basic temperature control in the space, while the ventilation system supplies 100% outdoor air via a displacement ventilation air distribution system, using a raised floor. The central ventilation air handlers of this building, and the building exhaust will provide heat recovery via air to hear exchangers. The thermo-active slab system uses the high thermal mass storage of the building structure to enable off-peak heat rejection using medium temperature water piped through the slabs. In cooling mode, the in-slab water temperature generally runs at approximately 64°F, thus a small chiller is needed. In heating mode slab, water temperature runs at 95°F, thus a small boiler is needed. This concept can work effectively if the building envelope is of a very high quality and performance. While the high performance building envelope could be seen as a premium cost to the project, the additional envelope capital costs were offset by savings in the mechanical system costs. This will result in a building HVAC system that would use 60% less energy than a conventional system, at no net premium cost to the project. The project team must properly design the exterior glazing properties to eliminate transient thermal zones around the perimeter of the building. The glazing is specified to have a high thermal resistance so it does not act as another radiant surface, working against the radiant slab temperature control system. This type of radiant cooling system, using the building structure as a thermal storage device, creates a near uniform indoor climate so that extensive local temperature controls are not needed. This system requires about 60% less controls than a conventional “all-air” HVAC system, but results in better indoor comfort conditions. Thermo-active slab systems have been used successfully in Europe for the last 20 years. Radiant energy/heat exchange takes place at the speed of light, and the huge thermal mass of the slab is self-compensating for variable cooling and heating loads in the space.

LATENT HEAT STORAGE FOR PROCESS HEAT APPLICATIONS

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Industrial process heat applications have been identified as a promising new area of application for thermal energy storage systems. Storage systems offer not only the reuse of thermal energy in cyclic processes which facilitates the integration of solar energy due to the availability of storage capacity. The bulk of process heat applications require steam at pressures between 1 and 20 bar with corresponding saturation temperatures between 100°C and 210°C. While the application of phase change materials (PCMs) is straightforward for isothermal energy storage, no commercial system is available in this temperature range today. The project PROSPER aims to develop cost effective PCM storage systems for process heat applications with a special focus on the concrete industry.

The main problem in the development of PCM storage systems result from the PCM’s low thermal heat conductivity, especially in the solid phase (characteristic value: < 1 W/K/m). Solutions to overcome the limited power density can be found by using composite materials of PCM mixed with graphite, integrated layers made of materials showing a high thermal conductivity or macro-encapsulation of the storage material.

For the construction of novel PCM steam accumulators, it is necessary to have tools to design the thermal behaviour of the steam accumulator. Using a tube register with externally arranged PCM, the number of tubes and their distance has to be defined, depending on the steam process the accumulator is integrated into. Within this work, appropriate simulation models are developed. Further validation of the models will be conducted using laboratory scale experiments.

Friday 4:20-6:00
Session 15A
UTES- General

DEVELOPMENT OF A DESIGN AND PERFORMANCE PREDICTION TOOL FOR THE GROUND SOURCE HEAT PUMP SYSTEM

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In order to promote ground source heat pump systems (GSHP) effectively into the market in Japan, the authors have developed a novel design and performance prediction tool for the GSHP system. The developed tool evaluates performance of the GSHP system with multiple ground heat exchangers. The tool also includes Life Cycle Analysis (LCA) and is suitable for the situation in Japan. Some advantages and features of this tool are described below,

1. A user-friendly data input procedure and graphical outputs based on MS Visual Basic program
2. A short period of time for two year's calculation according to hourly heating and cooling loads (Calculation time is less than 40 seconds for a typical notebook PC)
3. Contained database of CO_2 emissions, lifetimes and costs for various subjects can allow calculation of LCC (Life Cycle Cost) and $LCCO_2$ (Life Cycle CO_2).
4. A high-speed algorithm for calculation of thermal response of multiple ground heat exchangers
5. Available for short ground heat exchangers of big caliber by application of modification coefficients
6. Calculation of internal thermal resistance in a borehole according to tube geometric arrangement by BEM (Boundary Element Method).

In this paper, the outline of the calculation algorithm for calculation of the ground temperature and circulated fluid temperature for pipe arrangement is mainly explained. In addition, performance prediction of a residential GSHP system with steel foundation piles as ground heat exchangers was performed with the developed tool as an example.

CFD-BASED DESIGN AND CHARACTERIZATION OF HOT WATER SEASONAL HEAT STORES

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Proper characterization and intelligent design of thermal energy stores (TES) are major concerns of thermal engineers. Computational fluid dynamic (CFD) based design and characterization opens a new avenue in the development of new generation TES. It is especially suited for large sized and seasonally operating hot water heat stores (HWSHS), whose design based on the field or laboratory database is impractical. However, one requires a proved CFD procedure which adequately simulates the essential features of flow, turbulence and energy fields. The CFD model developed in Panthalookaran, et al. (2006) is found to closely simulate HWSHS and is conveniently used in the current study. Another requirement for CFD-based design analysis is a suitable characterization scheme which properly grades the performance of different storage processes. The earlier attempts of TES characterization over-emphasized either the First Law of thermodynamics resulting in an entirely energy-based characterization or the Second Law of

thermodynamics resulting in a purely exergy (entropy)-based characterization. The new method developed in this paper suitably integrates the First Law and Second Law concerns. The First law concern is incorporated into a quantity called energy response of TES and the Second Law concern into an entropy generation ratio. A product of these two quantities is at the heart of the new method. Two characteristic storage evaluation numbers (SEN) or efficiencies are defined for charging-discharging and storing processes respectively. The design analysis on HWSHS is carried out in two steps. In the first step the evolution of the flow and thermal fields of a typical HWSHS during charging-discharging or storing process are explored using a CFD model. The resulting temperature field is characterized based on SEN efficiencies in the second step. Two sample applications of CFD-based design and characterization of HWSHS are also presented in this paper. In the first example, the effect of aspect ratio and side angles of a typical HWSHS on its overall performance is studied using first SEN efficiency definition. In the second example, a storing process is analyzed in order to estimate the influence of wall material and thickness on HWSHS performance using the second SEN efficiency definition. The predictions are in the expected lines suggesting the usefulness of the new CFD-based design and characterization scheme.

Friday 4:20-6:00
Session 15B
PCM in Buildings

HEAT TRANSFER MODELLING WITHIN GRAPHITE/PCM COMPOSITE MATERIALS FOR HIGH TEMPERATURE ENERGY STORAGE

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Moderately compressed exfoliated graphite (CEG) leads to highly porous graphite “foams” or matrices which have numerous actual and potential applications. The graphite/salt composite materials considered here for high temperature energy storage applications, as due to its superior heat conduction and thermal storage characteristics, are manufactured by uniaxial compression of a mixture of salt powders and expanded natural graphite (ENG). Developing systems for thermal energy storage using these graphite/salt compounds implies understanding and simulation of heat transfer and phase change phenomena within such materials. As a result of the complexity of structure at the microscopic scale, modelling at this scale becomes essentially impossible. The difficulty arises from the need to write separate energy equations for the regions of graphite, salt melt, solid salt, and at every graphite/salt interface. Rather than attacking the problem in this way, the pore-scale information can be used to derive continuum macroscopic equations that are valid in all regions. This change of scale can be accomplished by the method of volume averaging [1]. However, information about the microscopic representative elementary volume is necessary to carry out the volume averaging procedure. The objective of this work is threefold: to identify space-time scales allowing representing the thermal behaviour of ENG/salts compounds by means of and effective homogeneous medium, to derive the governing energy equations, and to establish formal relationships between macroscopic physical properties of the ENG/salt materials and those of their components.

The present article is organized as follows. Simplified models and basic elementary cells for ENG/salt pore-scale morphology are proposed in the second section. It allows reproducing main structural and physical properties of the composite that are involved in the heat transfer within the graphite/salt matrix. In the third section, the governing equations and boundary conditions for phase change and heat transfer in a porous medium (pore-scale model) are spatially smoothed to produce continuum equations. Different tests are proposed in the fourth section to validate the theoretical results of the third section and to identify the time scales allowing homogenisation. The last section includes simulation and analyses for test results obtained for composites with different apparent CEG matrix density.