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Integration of Renewable Energy in the Built Environment (Electricity, Heating and Cooling)

Exploring potentialities of energy-connected buildings: performance assessment of an innovative low-exergy design concept for a building heating supply system

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Abstract

Low exergy building systems generate new possibilities for the design of high performance buildings, especially when the design of a new building is considered as part of a district where the relationship between buildings are optimized to minimize the dispersion of energy in the environment and maximize the recovery of waste energy. We present an innovative design concept and the performance assessment of the heating system of the new Embodied Computation Laboratory at Princeton University. The system is demonstrated to be able to match the heat demand without need for backup systems.

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Keywords: Low-exergy; TRNSYS; calibration; monitoring; cascade; radiant floor.

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Nomenclature

$\dot{m}$	mass flow rate [kg/hr]
OAT	Outside Air Temperature [°C]
RWT	Return Water Temperature [°C]
SWT	Supply Water Temperature [°C]
TF	Time fraction over one hour when the condensate is flowing to the tank [%]

1. Introduction and background

Low exergy building systems create more flexibility and generate new possibilities for the design of high performance buildings by matching the quality levels of heating and cooling systems. This enables the use of more moderate supply temperatures, which increase the system performance. The system optimizes the quantity of energy but also its quality. The benefits of a low-exergy approach are expanded if the design of a new building is not considered as stand-alone, but as part of a district. There buildings are interconnected and relationship between them is optimized to minimize dispersion of energy in the environment and maximize recovery of waste energy.

A low exergy district system is one that matches the quality of the energy across various demands in a community. The International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 64 on Low Exergy Communities studies techniques and cases for district systems that cascade the value of energy through the appropriate demands, thereby optimizing the exergy use [1], [2]. Low exergy systems at the building scale have been previously studied [3], and contribute to optimizing the demand at the community scale. For example, by using low temperature radiant heating in a building the temperature of the distribution of that heat in district heating system can be lowered independently of the heat demand. A building may have the same heat loss, but if the delivered temperature is lower for its systems, then the district heating network is not required to supply such a high temperature, which increases the efficiency of the network. Building heating only needs to keep buildings above roughly 20°C. When heat is available in cogeneration systems or from industry waste heat, the community strategy should be to use the high quality first where higher quality is demanded. Industrial demand generally sets the high temperature demand, and often its waste stream is warm enough for other heating systems at lower temperatures, which for buildings would themselves cascade first to water heating systems at 50°C and then to the space heating systems at lower temperatures. This cascade greatly increases the performance of the overall system [4].

The first district heating systems used high temperature and pressure steam as the working fluid. High temperature combustion of readily available fuel sources made this the most convenient system. Current pressures to reduce carbon emissions and increase efficiency have led to the evolution of district heating systems and their temperatures. The 2nd and 3rd generation district heating moved from steam to lower temperature hot water systems. Current research is aiming for 4th generation systems [5], which strive for the lowest temperature possible and optimize various sources such as low temperature geothermal heat.

1.1. A new building conception

We present an innovative concept for the heating energy supply to the new Embodied Computation Laboratory (ECL) shown in Fig. 1, located in the Princeton University campus. The lab is composed of a wooden structure main

Fig. 1. (a) site plan; (b) the chemistry building (left) and the new ECL building; (c) the glass pavilion

space (500 m^2 floor area, 6.5 m height) and a separate glass pavilion that was part of the old laboratory.

The objective of the work is to verify the design of a low temperature heating system (radiant floor) that is installed in the new building shown in Fig. 2b. This system exclusively relies on the waste energy (hot condensate water) resulting from the steam heating system of the nearby chemistry building and optimizes its operation to minimize the use of additional electricity. The higher temperature condensate is first used for heating of the glass pavilion.

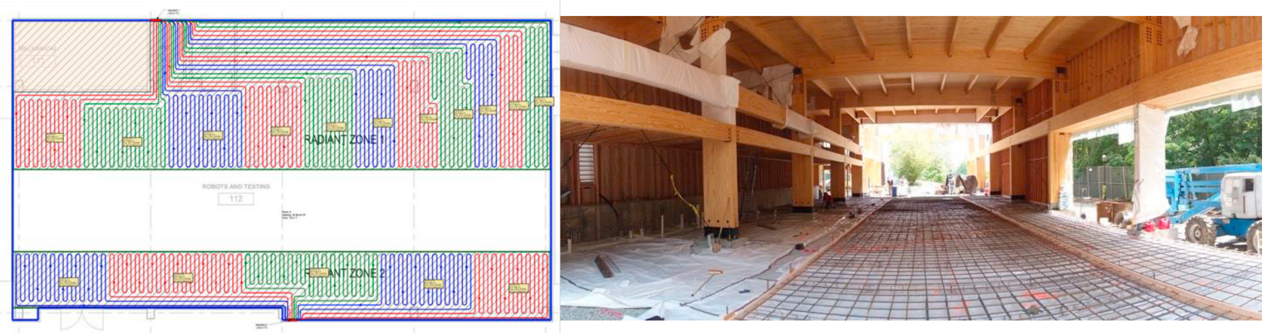


Fig. 2. (a) radiant floor layout in the main space (b) construction of the floor

2. Methodology

The system concept, as shown in Figure 3, is based on the thermal exchange between the hot condensate produced by the steam plant in the chemistry building and the heating system in the new ECL. The use of steam for energy supply in the chemistry building produces a certain amount of condensate water, which still has a high enough temperature for heating the new building. There is a natural synergy between the systems as the condensate produced by the chemistry building increases proportionally to the heat demand, and therefore is increased with colder temperatures when the heating demand for the lab also increases.

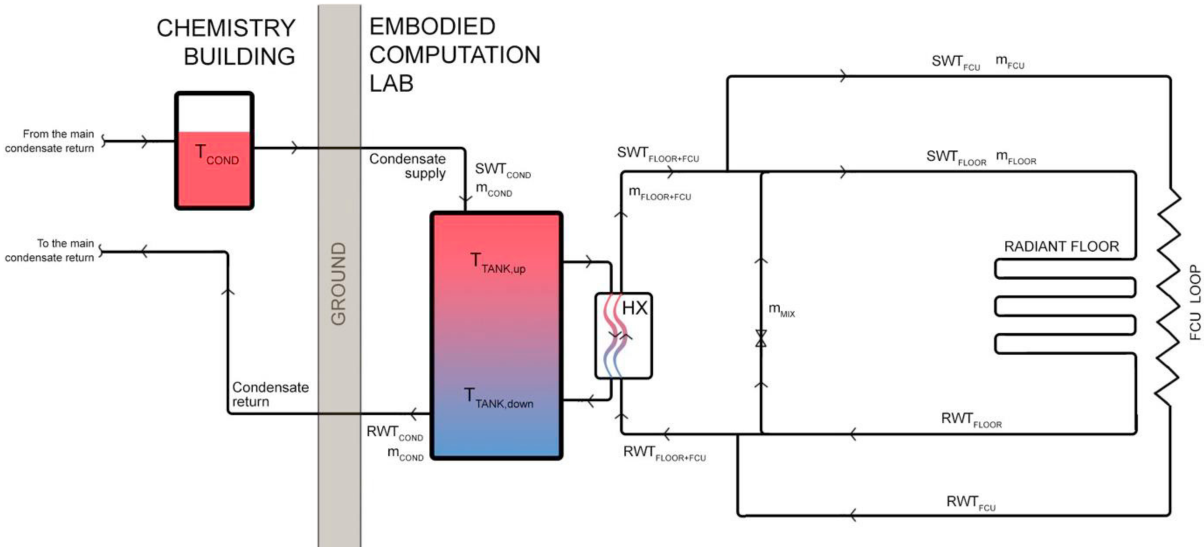


Fig. 3. Schematic diagram of the heating system

The condensate produced from the steam heating in the large air-handling units of the chemistry building is collected in a tank called condensate trap, which would usually flush the condensate into the return pipe of the district heating system. Instead a valve and piping system is installed that diverts the condensate into the ECL. When the tank is full, the condensate is pumped to the insulated heating tank in ECL. This tank is equipped with a backup electric heater to supply heat if the water temperature in the tank is too low. The tank is stratified and the cold water is sent back to the cogeneration plant, where the gas turbine efficiency is increased by having cooler condensate returned to the makeup water.

The condensate water in the ECL tank flows through a plate heat exchanger to deliver heat to the heating system. This includes two loops. One responds to the primary call for heating that delivers heat through a radiant floor and the other supplies high temperature heat to the glass pavilion and responds to a secondary call for heating through the activation of additional fan coil units in the main ECL space. A mixing valve controls the supply temperature of the radiant floor loop. The set point temperature to be maintained in the lower airnode of the main spaces is set to 20°C during the day and to 18°C at night, while in the pavilion the temperature has to be maintained above 16 °C.

Because the aim of the system design is to avoid the need of supplementary energy sources (such as the electric heater in the main tank), the amount of energy extracted by the condensate over a defined period τ should be equal to the amount of energy delivered to the building space to maintain the setpoint temperatures, where the storage tank should be properly designed to account for the non-simultaneous energy supply and demand. The Equation (1) reports the hourly-based energy calculation that was performed to assess the system performance

$$\sum_{\tau}[(SWT_{cond}\text{-}RWT_{cond}) \cdot \dot{m}_{cond} \cdot C \cdot TF] = \sum_{\tau}[(SWT_{FLOOR}\text{-}RWT_{FLOOR}) \cdot \dot{m}_{FLOOR} \cdot C + (SWT_{FCU}\text{-}RWT_{FCU}) \cdot \dot{m}_{FCU} \cdot C] + \Delta_l \qquad (1)$$

where m_{cond}, m_{floor} and m_{fcu} are respectively rated to 12490 kg/hr (55 gpm), 6814 kg/hr (30 gpm) and 11360 kg/hr (50 gpm), C is the specific heat capacity of water and Δ_l are the losses throughout the system.

2.1. Monitoring

A network of sensors was installed in the building. On the condensate side, sensors are placed for monitoring the temperatures of the condensate entering (SWT_{COND}) and exiting (RWT_{COND}) the main tank in ECL. In order to determine the amount of condensate flowing to the tank, because the condensate flow rate (m_{COND}) is constant but not continuous, sensors are placed on the electronics of the condensate trap flushing pumps to determine the operational time. On the demand side, sensors are placed for monitoring the supply and return temperatures and the flow rate in the radiant and FCU loops. Five thermostats are in the main space and the average of the five measurements controls the call for heating. The heating operation data analyzed was collected in the cold week from the 13th to the 20th of March, 2017, and the electric backup heater was disabled to study only the cascaded heat.

2.2. Simulation

We created a TRNSYS model to analyze the building and system performance. For this study we looked at the radiant system operation and calibrated it on the real data obtained by monitoring the first period of the system operation. The building was modeled through Type 56 (Multizone building). As shown in Fig. 4, the main space was divided in three thermal zones (mechanical room, restrooms and lab space). The lab space zone was divided in two vertical airnodes to account for thermal stratification within the space height. The radiant slab of the lower airnode of the lab thermal zone was modeled using the integrated active layers in Type 56 (Multizone building). For the model calibration purpose, the weather data obtained from the weather station were used. Based on the real data related to the condensate availability, the supply temperature of the radiant floor loop was used as input in the model

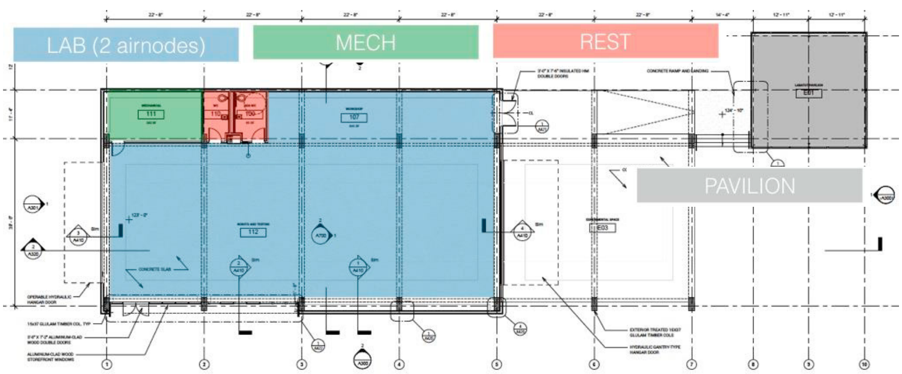


Fig. 4. ECL architectural plan and thermal zones used in the TRNSYS model

and an optimization-based calibration procedure [6] was performed both on the building design model and on the radiant floor features so that the simulated floor return water temperature and the simulated air-node temperatures match the measured data.

3. Results

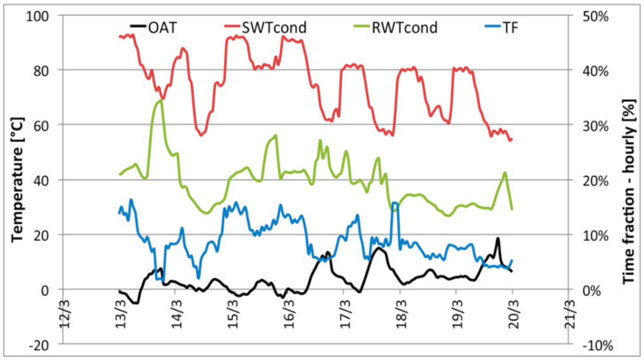
3.1. Condensate availability

The condensate delivery from the condensate trap tank was evaluated using the sensor network to give an availability profile linked to outside conditions, which showed that the condensate tank flushed once every couple minutes and it took around 15 seconds to flush, and both the temperature and frequency of these flows varied with outdoor conditions that drive heat demand for the air handling system in chemistry. As Fig. 5a reports for a cold week in March 2017, the supply and return temperatures (SWT_{cond} and RWT_{cond}) between the condensate trap tank and the ECL tank,along with the time-frequency TF with which the condensate trap tank is flushed after filling (TF) are linked to outside air temperature (OAT). Lower outside OAT generates higher SWT_{cond} and TF.

The condensate return temperature (RWT_{cond}) also increases when the outside temperature decreases, which indicates that the increased heat loss from ECL due to lower OAT is compensated for by increased condensate from the chemistry building. The RWT_{cond} is subject to more variability as shown in Fig. 5a, and may also be influenced by lack of changes in the stratification of the tank or other extraneous loads.

3.2. Model calibration results

The measured radiant floor supply was used as input for the simulation and return temperatures were simulated and compared to measured values, as shown in Fig. 5b. The mean difference between measured and simulated return temperature (DIFF%_S-M in Fig. 5b) is around 3%, which is close to the temperature sensors accuracy (Acc_MEAS in Fig. 5b). The calculated calibration indexes fall within the commonly accepted range [6] (Mean Bias Error MBE= 2% and Coefficient of Variation of the Root Mean Square Error Cv(RMSE)=3%). This indicates that the set up TRNSYS model results as a reliable tool for properly describing the radiant heating slab behavior, and confirms the ability of the radiant slab to cover the heat demand with low temperature supply and return.



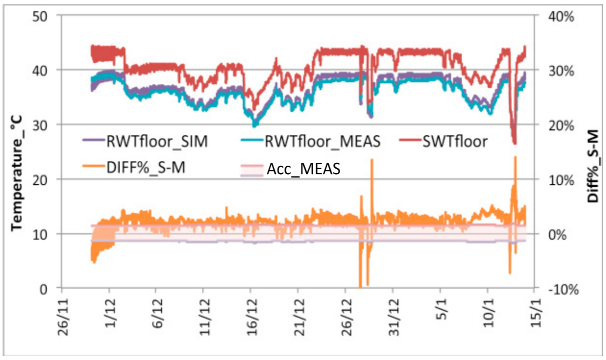


Fig. 5. (a) Condensate availability over a cold week in March 2017. (b) Radiant floor supply and return (simulated and measured)

3.3. System performance assessment

The system temperatures and energy balance are reported in Fig. 6. The temperatures in the main radiant heated space were maintained above the setpoint temperatures, except for one opening of the large 10x8 m hanger doors to observe the response of the system from a flush of cold air. The tank and the floor help buffer these extreme loads.

Fig. 6 shows the condensate supply and the energy delivered to the space following similar profiles, where the non-simultaneity between energy supply and demand is minimal. The red line (kWh_cond) represents the energy extracted hourly from the condensate (the left term in Equation 1). The orange line (kW_DELIV) indicates the total energy delivered to the ECL building through both the radiant floor and the FCU loops (calculated according to the right term of Equation 1).

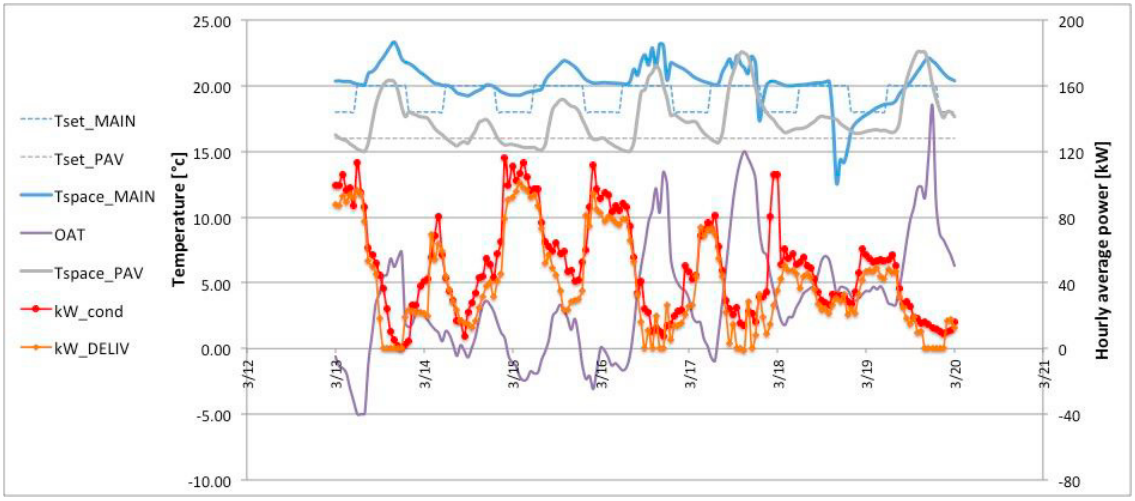


Fig. 6. Space temperatures in the ECL main space and pavilion (setpoint and measured), outside air temperature,

4. Discussion and Conclusion

The analysis demonstrates the utilization of waste heat from a laboratory building for low temperature radiant slab heating. Variability of supply quantity and quality present challenges for system optimization, but the common relationship of both building systems to outdoor air-conditions creates a positive feedback for heat load matching. The simulation of the radiant floor provides a dynamic tool to verify the heat stored in the floor, and can be leveraged in future work to better predict the thermal inertia of the system and optimally leverage available waste heat. Finally, the energy balance analysis demonstrates the ability of the system to match the heat demand using the varying condensate supply inputs, and operation without need for backup systems.

Future studies will focus on the prediction of more detailed system behavior with novel feedback control of radiant heat transfer and with better modeling and sensing of the air space stratification and floor interaction. Also, a novel reversing deep thermal gradient geothermal system for direct heating or cooling into the system will be compared as an alternative input into the cascade system.

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References

[1] Schmidt D, Kallert A, Sager-Klauss C. Optimising Community Energy Supply with Exergy Principles. CLIMA 2016 - proceedings of the 12th REHVA World Congress, Aalborg, Denmark, 2016.
[2] Jansen S, Meggers F. Addressing Different Approaches for Evaluating Low-Exergy Communities,” in CLIMA 2016 - proceedings of the 12th REHVA World Congress, Aalborg, Denmark, 2016.
[3] IEA ECBCS Annex 49, “Low Exergy Systems for High-Performance Buildings and Communities,” ECBCS AECOM, Frauenhofer Institute for Building Physics, 2010.
[4] Fang H, Xia J, Zhu K, Su Y, Jiang Y. Industrial waste heat utilization for low temperature district heating. En Policy 2013;62:236–246.
[5] Lund H et al. 4th Generation District Heating (4GDH). Energy 2014; 68:1–11.
[6] Fabrizio E, Monetti V. Methodologies and Advancements in the Calibration of Building Energy Models. Energies 2015;8:2548–2574.