Final report

1.1 Project details

Project title	IEA ECBCS - Annex 59 Minimizing Temperature Differences in Heating, Cooling and Ventilation Systems
Project identification (program abbrev. and file)	EUDP- 64012-0110
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Center for Indeklima og Energi, DTU.BYG Nils Koppels Alle 402, 2800 Kgs. Lyngby Bjarne W. Olesen
Project partners	Danmarks Tekniske Universitet Aalborg Universitet
CVR (central business register)	30 06 09 46
Date for submission	01/08/2016

1.2 Short description of project objective and results

English:

This project, Annex 59 - High Temperature Cooling and Low Temperature Heating in Buildings, was a part of International Energy Agency (IEA)'s Energy in Buildings and Communities Programme (EBC).

The project developed a novel method to analyze HVAC (heating, ventilating and air-conditioning) systems in buildings in order to minimize temperature differences within systems and within indoor terminal units and the indoors. High temperature cooling and low temperature heating systems (e.g. water-based radiant heating and cooling systems) have been identified as the optimal heating and cooling systems to achieve superior energy- and resource-efficiency, and environmental friendliness.

The results of the project and the developed design and analysis methods are beneficial for HVAC system designers, consulting engineers, researchers, and manufacturers of heating and cooling equipment.

Danish:

Nærværende projekt, Annex 59 – Høj temperatur køling og lav temperatur opvarmning i bygninger, var en del af International Energy Agency (IEA)'s Energy in Buildings and Communities Programme (EBC).

Via projektet er der fundet en ny metode til at analysere HVAC systemer (opvarmning, ventilation og air-conditioning) i bygninger medhenblik på at minimere temperaturforskellen i mellem systemerne og mellem indvendige terminal systemer og indendørs. Høj temperatur køling og lav temperatur opvarmningssystemer (f.eks. vandbaseret strålings varme og kølesystemer) anses for at være de mest optimale varme og kølesystemer for, at opnå en større energi og ressource effektivitet, samt mest miljøvenligt.

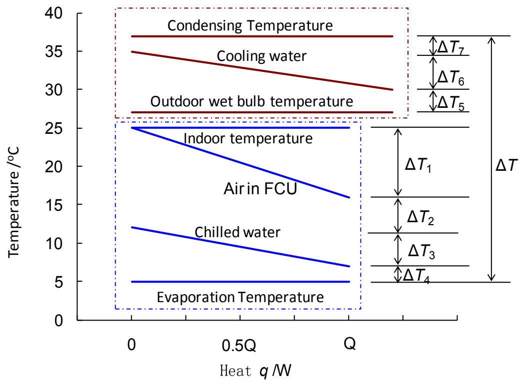
Resultater opnået ved projektet, det udviklede design samt analysemetoder er brugbare for HVAC system designere, rådgivende ingeniører, forskere samt producenter af opvarmning og kølesystemer.

1.3 Executive summary

The main purpose of buildings and HVAC systems is to maintain a comfortable and healthy indoor environment, including required levels of temperature, humidity and indoor air quality. Theoretically, any heating source with a higher temperature than the indoor environment can supply heat in winter and vice versa for cooling sources in summer. Since the temperature of heating sources and cooling sources influences HVAC system energy use directly, high temperature cooling and low temperature heating systems have the potential of increasing energy efficiency and, hence, increasing energy savings. The concept of reducing the temperature difference between heating/cooling sources and the indoor environment typically involves increasing the dimensions of heat exchange surfaces. Independent control of temperature and humidity is another important aspect of high temperature cooling and low temperature heating approach.

Previous EBC projects, such as Annex 37 (Low Exergy Systems for Heating and Cooling of Buildings) and Annex 49 (Low Exergy Systems for High Performance Buildings and Communities), dealt with the HVAC system from the aspect of second-law efficiency. According to their results, to raise the exergy efficiency of an HVAC system, the temperature difference between the output of the heating/cooling plant and the conditioned indoor temperature should be reduced. However, how could we reduce this temperature difference?

This project focuses on the loss of temperature difference throughout the whole HVAC system. As shown in Fig. 1, in a typical summer condition, the temperature difference between indoor temperature and outdoor wet bulb temperature is only 2 K, however, the temperature difference between condenser and evaporator of chiller is 32 K. The temperature difference is mainly consumed during the heat transportation process from the cooling/heating sources to the indoor space, and from the condenser to the outdoor environment. In a conventional HVAC system as shown in Fig. 1, air is dehumidified by condensation during cooling the air, which requires the cooling source’s temperature to be lower than the indoor dew point temperature, much lower than what is theoretically required for the indoor space cooling load. The coupled process of cooling and dehumidifying will result in the loss of temperature difference in an HVAC system. In addition, temperature difference loss exists inside the conditioned indoor space, due to the contradiction of the unified temperature of supplied air and various grades of heat and moisture source in buildings.



(a)

Temp. Difference	Heat/ Mass transfer area	Transportation energy consumption	Compressor energy consumption
ΔT_1	-	FCU Fan	-
ΔT_2	FCU	-	-
ΔT_3	-	Chilled water pump	-
ΔT_4	Evaporator	-	-
ΔT_5	Condenser	-	-
ΔT_6	-	Cooling water pump	-
ΔT_7	Cooling Tower	-	-
ΔT	-	-	Compressor

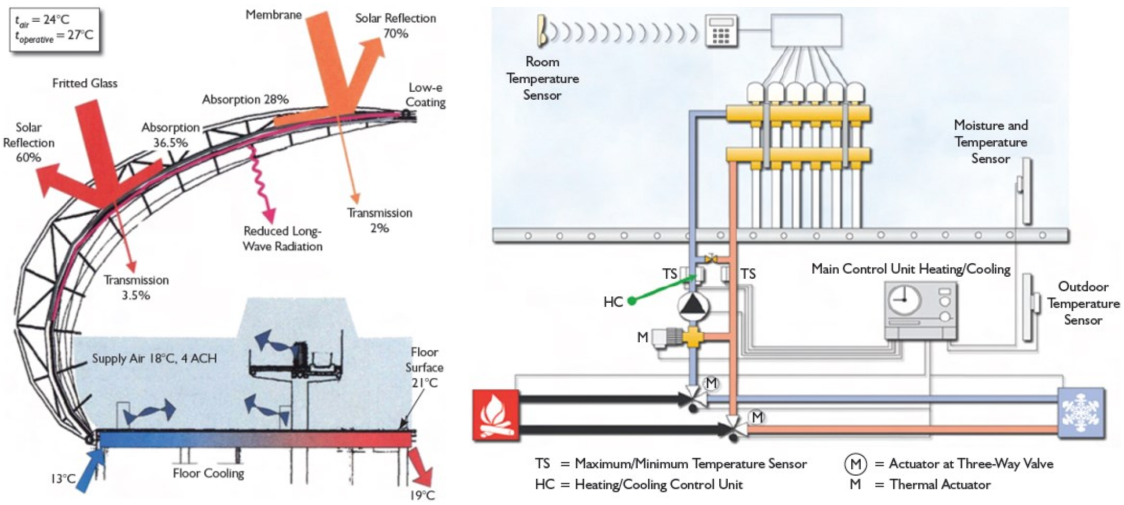
(b)

Fig. 1. Temperature difference consumed by heat exchange and transmission in a typical HVAC system: (a) schematic diagram, (b) temperature difference of each sub-process.

The losses in temperature difference can be classified into three types: by heat exchange (moisture included), by heat transmission through air/water circulation, and by indoor terminals that emit or remove heat to or from the conditioned indoor space. The handling process of HVAC system, as well as indoor terminals, is the key factor for reducing temperature difference and achieving high temperature cooling and low temperature heating. In this project, indoor terminals refer to devices releasing heat/cold to the conditioned spaces in particular. Different choices and arrangements of indoor terminals will result in different requirements of heating source and cooling source given the same need of thermal indoor environment. Reducing heat exchange temperature difference and removing unnecessary heat exchange is the main approach of high temperature cooling and low temperature heating, which can be realized by proper indoor terminals integrated in HVAC systems. Lower temperature of heating sources and higher temperature of cooling sources benefit heat supply system and refrigeration system respectively, and expand feasibility of using natural heating and cooling sources.

According to exergy analysis, any mixture of cold fluid and hot fluid will cause mixture loss and additional energy use. In large space buildings (e.g. railway stations, airports, etc.), cold air supplied by jet ventilation is used to remove the entire extra heat of the building, despite there exist rather different grades of heat. Fig. 2 shows an HVAC system for a large space building aiming to avoid mixture loss by controlling the stratification of air and application of radiant floor. The supply/return water from chiller is 5°C/14°C, and supply/return water from radiant floor is

13°C/19°C. Same cooling source is introduced into air handling unit and radiant floor, which shows an energy saving potential if a high temperature chiller is used.



(a) (b)

Fig. 2. HVAC system for a large space building: (a) design concept, (b) control concept.

Energy offset of cooling and heating, dehumidifying and humidifying by coupled process of sensible load and moisture load, results in significant energy waste. One example is that in areas with a dry climate, the outdoor air is already dry enough so the dehumidification of fresh air is not necessary. Separated processing of sensible load and latent load (moisture), named temperature and humidity independent control (THIC) system, can avoid such energy offset. In addition, taking condensing dehumidification with re-heater as an example, when the same supply air with rather lower temperature is introduced into many different rooms, the airflow modulation could hardly maintain the required indoor condition, hence reheat has to be introduced to meet the temperature requirements of the rooms rather than control indoor humidity. In high temperature cooling and low temperature heating systems, as an additional benefit of the required high flow rate of indoor terminal devices, the possibility of the temperature difference among rooms will decrease. The widespread use of HVAC systems based on low temperature heating and high temperature cooling allows greater potential of exploitation solar energy and development of relevant technologies, which will contribute to implementing the EU 20-20-20 policy.

Based on the current situation of HVAC systems, this project developed a novel analysis method in order to minimize the temperature differences in heating, cooling and ventilation systems in buildings. The findings of this project and the developed design and analysis methods are beneficial for HVAC system designers, consulting engineers, researchers, and manufacturers of heating and cooling equipment.

1.4 Project objectives

A thorough comprehension of HVAC systems from the perspective of reducing mixture loss and transfer loss is desired. Based on the profound understanding of HVAC system, the concepts of avoiding energy offset of cooling and heating, humidifying and dehumidifying, mixture of cold fluid and hot fluid, and transfer loss due to unnecessary or inappropriate heat exchanges were the principles. Therefore, the project was organized following the idea of reducing mixture loss and transfer loss, and the subtasks were arranged in response to the current insufficiency or inadequateness of HVAC systems.

The main objectives of the project can be summarized as following:

- Establish a methodology for analysing HVAC systems from the perspective of reducing mixing and transfer losses,
- Propose novel designs for indoor terminal units and novel flow paths for outdoor air handling equipment, and
- Develop high temperature cooling and low temperature heating systems in buildings with fully utilized heat and cold sources, high efficiency transportation and appropriate indoor terminal units.

The ultimate goal of the project was to build up the concept of surveying HVAC systems from the perspective of reducing mixture loss and transfer loss then apply it in analysis of actual energy saving technologies.

In order to reach this goal, an international collaboration on different issues was needed: a deep and comprehensive investigation to evaluate current situation, summarize the appropriate and inappropriate design of HVAC systems, unify and clarify the research methodology, discuss the basic settings and methodology of simulation and testing, research on key parameters of radiant terminals, study energy saving potential and limitation of radiant terminals combined with fresh air system, and research on HVAC indoor terminals for large space buildings including radiant floor and supply air terminals.

It is clear that the basis for a meaningful and profitable research on indoor environment control is a thorough understanding of building thermal environment system. To reduce mixture and transfer loss, and, therefore, to minimize ΔT in HVAC systems, the four subtasks in the project were arranged accordingly as shown in Fig. 3, including principles and methodology, indoor environment and terminal devices, outdoor air handling processes and total system analysis.

In methodology, the basic concepts and definitions as well as research and investigation methods were unified and clarified. Based on low temperature heating and high temperature cooling approach, the appropriate and inappropriate design of HVAC systems were investigated and summarized. A deep and comprehensive investigation was needed to evaluate the current situation.

One of the most important characteristics of indoor built environment is to remove heat and moisture from indoor to outdoor. When driving force ΔT (temperature difference) is not sufficient, a heat pump is necessary in the system to supply extra ΔT. Effective use of ΔT, such as a matching flow rate, is closely related to system energy efficiency. The following subtasks are important demonstrations and applications of the proposed methodology. Radiant terminals, including radiant floor, radiant ceiling etc. can reduce heat exchange segments between indoor environment and heating/ cooling sources, which are promising solutions for low temperature heating and high temperature cooling. Research on key parameters of radiant terminals and the potential of combining radiant terminals with convective terminals devices was an important part of this project. Dynamic behavior of radiant floor cooling systems under direct solar radiation was also investigated. Dehumidification methods in both dry and humid outdoor climate, including desiccant dehumidification, condensation dehumidification, and dual-temperature system were also researched and optimization suggestions were identified.

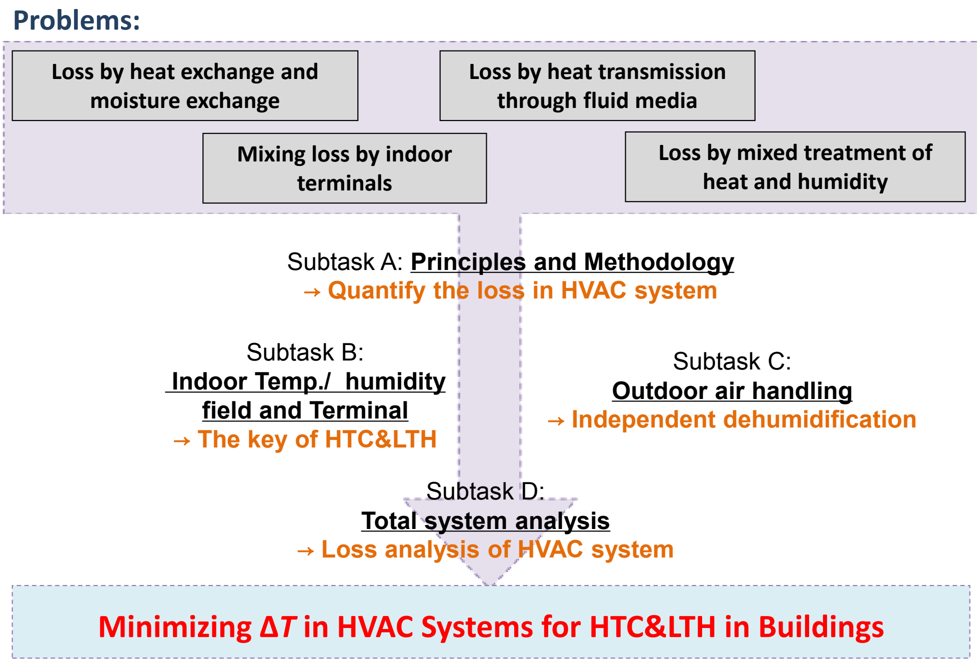


Fig. 3. Organization of subtasks.

1.5 Project results and dissemination of results

The project was organized so that there were four different subtasks. Each subtask produced a report, in addition to a summary report and a report based on exemplary case studies.

The following list summarizes the deliverables from each subtask:

Subtask A report: "Guide book of new analysis method for HVAC system". Current air-conditioning systems in different countries are summarized from the perspective of temperature difference. Entransy dissipation is proposed to investigate the transfer characteristics of air-conditioning system as well as equivalent thermal resistance. The novel analysis method is put forward for theoretical research.

Subtask B report: "Demand and novel design of indoor terminals in high temperature cooling and low temperature heating system". Terminal handling process is investigated from the perspective of removing indoor heat and moisture. Objectives for terminals are then proposed with the help of entransy dissipation analysis and *T*-*Q* diagrams. Radiant terminal is also investigated, which is treated as an appropriate approach to achieve high temperature cooling and low temperature heating.

Subtask C report: "Novel flow paths of outdoor air handling equipment". Air handling processes for heat recovery and dehumidification are both investigated. Entransy dissipation and unmatched coefficient are utilized to investigate the coupled heat and mass transfer processes between air and liquid desiccant or solid desiccant. Novel process for handling humid air is also proposed.

Subtask D report: "Design guide for high temperature cooling and low temperature heating systems". Influences of temperature level on energy performances of heating/cooling sources are investigated. A demonstration building is chosen to compare the performances of conventional system and high temperature cooling and low temperature heating systems. Approaches to set up high temperature cooling and low temperature heating systems are proposed. Operating performances as well as energy use of high temperature cooling and low temperature heating systems in different buildings are investigated.

The final reports will be available at the project homepage, once the final reports are approved by the executive committee (ExCo) of IEA EBC.

During the project, there have been several dissemination activities and the project group has been very active in promoting the project and its results. There have been several presentations, workshops and special technical sessions in scientific conferences, and invited talks. Numerous conference papers and articles in scientific journals have been published. Examples of these activities are given in Appendix A and a full list of publications by the project participants can be found in Appendix B.

1.6 Utilization of project results

This project studied the currently existing heating, cooling and ventilation systems and provided improvement suggestions.

The core task of establishing a suitable indoor temperature and humidity environment is to remove the extra heat and moisture from the indoor to outdoor. This process is regarded as a complex system consisting of passive building envelopes and active air-conditioning systems. In this process, the indoor cooling/humidity load can be removed from the indoor environment to the outdoor environment passively through building envelopes, including heat transfer and infiltration. The driving force of the heat transfer through the building envelope is the temperature difference, which is determined by the indoor and outdoor conditions. When the temperature of the outdoor condition is not low enough, power input is required to provide a temperature difference between the indoor and outdoor environments for removing heat or moisture in the HVAC system.

The large temperature difference of actual air-conditioning system is restricted by the integrated processes for handling sensible load and moisture, by the performance of actual chillers, and by the energy use of fans and pumps and the input heat or mass transfer capacity. Energy efficiencies of the heating/cooling sources are related to the operating temperature levels. By reducing the temperature differences existing in the various transfer processes, high temperature cooling or low temperature heating system could be realized accordingly, which provides superiority to improve energy performances of cooling/heating sources.

The basic concepts and definitions as well as research and investigation methods should be unified and clarified. Entransy is a thermal parameter to analyze the heat transfer process. Through the entransy dissipation and the equivalent thermal resistance, the characteristic of the heat transfer process could be depicted effectively. Reducing the entransy dissipation helps decreasing the driving temperature difference of passive systems such as building envelopes with a fixed load.

A sub-group within the project focused on the indoor temperature and humidity fields and indoor terminal units. Indoor terminal units are active building components that emit or remove heat and/or moisture to indoor spaces. These indoor terminals mainly rely on convection (natural or forced), radiation or both. Before the characteristics of the terminal units are studied, the indoor heat and moisture sources should be clearly identified. Current literature and data were used to gather information about indoor heat and moisture sources, and also about the indoor terminal units. Case studies and the novel system applications were gathered with the help of project participants. In addition to the energy performance analyses of these systems, entransy analyses were used to evaluate the chosen terminal units and heating, ventilation and air-conditioning (HVAC) systems in order to identify the possibilities of improving the existing terminal units and systems.

According to the entransy dissipation analysis, there are two aspects to be considered in removing indoor heat. The first is to reduce the heat removed by the terminal units (for example to reduce the heat transfer through building envelope in summer), and the second is to increase the required temperature of cooling source for cooling (lower the heating source's temperature for heating). Thus, the high temperature cooling and low temperature heating system is an efficient approach to achieve an optimized terminal process with lower entransy dissipation. Radiant heating and cooling system is regarded as an important approach to set up a high temperature cooling and low temperature heating system. Characteristics of radiant terminals were investigated including their variant dynamic behaviors under the impact of intermittent operation and transient solar radiation. The detailed analysis on dynamic performance and cooling capacity prediction of radiant terminal, aiming to clarify the radiant terminal's characteristics, provides guidance for practical applications.

The original intention of supplying outdoor air is to meet the occupants' health requirement. Due to different conditions of indoor air, outdoor air may increase cooling/heating and dehumidifying/humidifying load. Outdoor air handling process or air humidity handling process is a key issue in achieving high temperature cooling and low temperature heating in buildings. How to choose the appropriate approaches for humid air handling process, how to evaluate the energy performances of air handling processors and how to improve the processors' performances were studied. To evaluate the energy performance of different air handling processes, Coefficient of Performance (COP) was chosen as the index for comparison, which is defined as the obtained heat/cooling capacity divided by the input power. For example, it is the fan power for a plate enthalpy exchanger while the consumption include the compressor's power for a heat pump driven liquid desiccant air handling processor. The suitability is investigated for heat recovery device in typical cities based on the COP. For different humid air handling approaches, performance improving solutions were analyzed. To improve the energy performance of the air handling process using solid or liquid desiccant, it is recommended during the air handling process to proceed along the iso-concentration line (or iso-relative humidity line) rather than the isenthalpic line. Constructing a multi-stage process for the humid air handling process is a feasible approach to increase the required cooling source temperature (for condensation dehumidification method) or lower the required regeneration heating source temperature (for desiccant dehumidification method).

The mission of an air-conditioning system is to remove heat or moisture from indoor sources to an appropriate outdoor sink. It is composed of indoor terminal, heat transfer process, coupled heat and mass transfer processes, etc. Entransy analysis helps to cast light on the essence of the air-conditioning system. Entransy is an appropriate theoretical tool to identify the dissipation process and optimize the heat transfer processes in the air-conditioning system. Energy efficiency of the heating/cooling sources is also related to the operating temperature levels. By reducing the temperature differences in the various transfer processes, a high temperature cooling or low temperature heating system could be realized, which improves the energy performance of cooling/heating sources. The theoretical tools based on entransy analysis were applied in real buildings for performance optimization. Applications of entransy analysis in data centers with high-density sensible load, office buildings and large space buildings were selected as case studies. Reducing the entransy dissipation in transfer processes helps to achieve high temperature cooling and low temperature heating of the air-conditioning system, which is beneficial for improving the energy efficiency. These case studies are beneficial for researchers, designers, consulting engineers and equipment manufacturers to have a full understanding on this Annex project. These analyses also help to understand the essence of indoor thermal built environment.

The results of the project will strengthen the expertise, which is already available, of the participating partners in the global field of heating, cooling, and ventilation research. The publications of the results will also help to sustain the position of leading the research within this field.

The results of the project can have global implications if adopted by the HVAC system designers, consulting engineers, and policy makers. The results of the project clearly show the way to follow regarding the heating, cooling, and ventilation system design in different building types and in different climates. The low temperature heating and high temperature cooling approach results in significant energy savings compared to conventional heating and cooling systems used today, and this approach also enables the integration of renewable energy resources into building heating and cooling systems. This is a crucial aspect since it would allow replacing the fossil fuels often used in building heating and cooling systems.

The transition from conventional heating and cooling systems to novel heating and cooling systems will have remarkable effects on the national and international energy flows, energy infrastructure, and on greenhouse gas emissions. Further studies are required to quantify the energy and greenhouse gas emission savings potentials on a larger scale.

The project was a part of a PhD project with the title "Low temperature heating and high temperature cooling in buildings" by Ongun Berk Kazanci at the International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark. He was actively involved in the project and worked particularly in Subtask B of the project. Some of his results from the PhD project were included in Annex 59. He has written articles based on his results and presented his findings in several international scientific conferences. His PhD thesis will be publicly available after September 2016.

1.7 Project conclusion and perspective

During the project, the state-of-the-art of heating and cooling systems in each participant country was summarized. Further analyses on different heating and cooling systems were done so that the improvement possibilities based on the current status can be identified.

The international participation in the project enabled to have a global view of the current situation in building heating and cooling systems in different countries. This also enabled to study the proposed novel systems in a broad range of climatic conditions, which makes the results of the project widely applicable.

The results of the project identified the low temperature heating and high temperature cooling approach as the optimal approach for heating and cooling buildings. In these systems, the heat transfer medium (usually water) has temperatures that are close to room temperatures. Water-based radiant heating and cooling systems (floor, wall or ceiling heating and cooling) are the most well-known example of low temperature heating and high temperature cooling systems.

Radiant systems have several benefits over conventional heating and cooling systems, in terms of energy efficiency (lower required peak heating or cooling plant capacities, higher performance of boilers, heat pumps, chillers and so forth), providing optimal thermal comfort for the occupants (uniform temperature distribution in spaces, avoiding noise and draught from air-based systems and so forth), and possibility of integrating renewable energy resources (ground, lake or sea-water, nocturnal radiative cooling and so forth) into building heating and cooling systems.

One particular application and interest for applying radiant floor cooling systems has been identified in the project as in spaces with large glazing façades (railway stations, airports, atria, etc.). In spaces with large glazing façades, there is usually direct solar radiation on the floor and the cooling capacity of radiant floor cooling systems increases considerably when there is direct solar radiation on the floor surface. The floor cooling systems provide cooling immediately (as soon as the solar radiation hits the floor surface), before the air in the space heats up. In contrast to the most common way of cooling these type of spaces (cold air supply with jet ventilation), using radiant floor cooling systems lowers the requirements for airflow rates (main cooling effect by the floor cooling system, and benefiting from the natural thermal stratification of the air by providing conditioned outdoor air to the occupied zones of the indoor space) results in considerable energy savings of up to 30 to 35%.

Separate treatment and control of sensible and latent loads (temperature and humidity independent control, THIC) was identified as another key approach to achieve energy efficiency and considerable energy savings. In this approach, radiant heating and cooling systems play a crucial role: the radiant heating and cooling system provides the major part of the sensible heating and cooling and the air handling unit or a dedicated outdoor air system (DOAS) provides the required amount of conditioned fresh air. This approach enables down-sizing the chillers or heat pumps that serve air handling units, and enable to use the high temperature cooling approach.

In general, building heating and cooling systems consist of three main parts: generation (heating and cooling plant), distribution, and heat emission or removal (indoor terminal units). It is crucial to consider all three parts of a system together and to optimize the performance of the whole system. The choice of indoor terminal unit is a critical process since the choice of indoor terminal unit directly affects the indoor conditions (thermal and acoustic) and the energy performance of the whole system, together with the possible heating and cooling sources that can be used.

Annex 59 project presented a new perspective and a new concept to analyze the HVAC system in buildings. The project followed the idea of reducing mixture loss and transfer loss, and the subtasks were arranged in response to the current insufficiency or inadequateness of HVAC systems. In the project, the methodology of entransy assessment in HVAC systems, which was one of the main items within Annex 59 activities, was described and applied. This represents a significant step towards a more extensive application of this method for HVAC systems. Further applications of this assessment method (e.g. storage, control, cascading concepts) will help identifying optimum and suitable uses of the analyzed technologies, and represents a promising field where further research is needed. The research is beneficial to set up a high temperature cooling and low temperature heating system for buildings, leading to lower primary energy consumption and greenhouse gas emissions in a global scale.

Appendix A – Project participants and activities

Project homepage: http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-59/ and http://www.annex59.com/

Operating Agent: Yi Jiang
Professor, Dean of Building Energy Research Center, Tsinghua University

Subtask Leaders:
Subtask A: Yi Jiang (Tsinghua University), Stefano Paolo Corgnati (Politecnico di Torino)
Subtask B: Bjarne W. Olesen (Technical University of Denmark)
Subtask C: Masaya Okumiya (Nagoya University), Xiaohua Liu (Tsinghua University)
Subtask D: Vincent Lemort (University of Liège), Marco Perino (Politecnico di Torino)

Annex 59 participants

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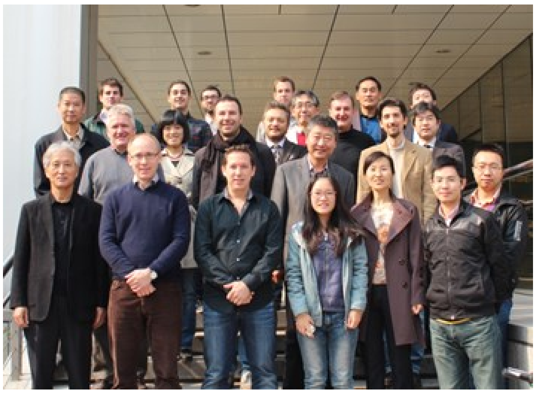
Activities

Since 2012, 8 workshops have been held for Annex 59, twice a year. Open forums have also been held during several international conferences, such as ISHVAC (2013), ASHRAE Annual Conference (2014), IBPC (2015), CLIMA 2016 (2016).

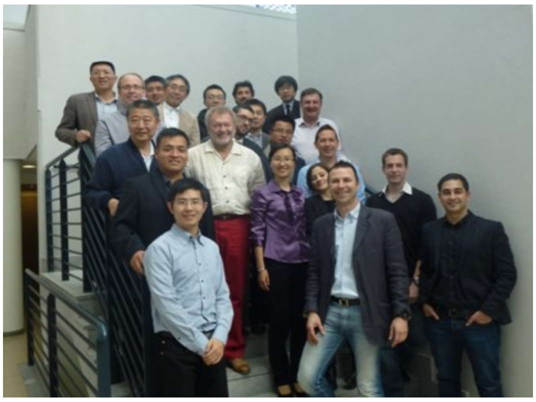
	Date	Place
1st workshop	Apr. 30th - May 1st, 2012	Aalborg University, Aalborg, Denmark
2nd workshop	Nov. 1st - Nov. 2nd, 2012	Zhuhai, China
3rd workshop	Apr. 17th - Apr. 18th, 2013	University of Liège, Liège, Belgium
4th workshop	Oct. 16th - Oct. 17th, 2013	Tsinghua University, Beijing, China
5th workshop	Apr. 14th - Apr. 15th, 2014	Politecnico di Torino, Torino, Italy
6th workshop	Oct. 13th - Oct. 14th, 2014	Nagoya University, Nagoya, Japan
7th workshop	Jul. 18th - Jul. 19th, 2015	Politecnico di Torino, Torino, Italy
8th workshop	Oct. 26th - Oct. 27th, 2015	Tsinghua University, Beijing, China

Fig. A-1. Group photo of the second expert meeting in Zhuhai, China.

Fig. A-2. Group photo of the third expert meeting in Liège, Belgium.



4th workshop in Beijing, China



5th workshop in Torino, Italy

6th workshop in Nagoya, Japan

7th workshop in Torino, Italy

Fig. A-3. Group photos selected.

Appendix B – Annex 59 related publications

The following is a list of scientific publications by the participants of Annex 59. The publications from the Danish researchers are underlined.

Subtask A

[1] Lun Zhang, Xiaohua Liu, Kang Zhao, Yi Jiang. Entransy analysis and application of a novel indoor cooling system in a large space building. International Journal of Heat and Mass Transfer. 2015, 85: 228-238.

[2] Tao Zhang, Xiaohua Liu, Zhen Li, Jingjing Jiang, Zhen Tong, Yi Jiang. On site measurement and performance optimization of the air-conditioning system for a datacenter in Beijing. Energy and Buildings. 2014,71: 104-114

[3] Lun Zhang, Xiaohua Liu, Yi Jiang. Application of entransy in match property of liquid desiccant dehumidification. Proceedings of the 15th International Heat Transfer Conference. August 10-15, 2014, Kyoto, Japan.

[4] Lun Zhang, Xiaohua Liu, Yi Jiang. Application of entransy in the analysis of HVAC systems in buildings. Energy. 2013, 53: 332-342.

[5] Tao Zhang, Xiaohua Liu, Yi Jiang. Match properties of heat transfer and coupled heat and mass transfer processes in air-conditioning system. Energy Conversion and Management. 2012, 59: 103-113.

[6] Capozzoli Alfonso, Corgnati Stefano, Fabrizio Enrico, Monetti Valentina, Perino Marco, Serale Gianluca. Sistemi impiantistici ad alta efficienza energetica operanti con basse differenze di temperatura: abaco delle soluzioni, metodi di dimensionamento e nuove tecnologie (IEA – EBC Annex 59), Report RdS/PAR2013/110, ENEA, September 2014.

Subtask B

[1] Kang Zhao, Xiaohua Liu, Yi Jiang. Cooling capacity prediction of radiant floors in large spaces of an airport. Solar Energy. 2015, 113: 221-235.

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