

Heat pump design student project applies thermal and thermodynamic theory to real life engineering work

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Abstract

Engineering students get separate courses on different topics. In the thermal and thermodynamic field this comprises e.g. Engineering Thermodynamics and Heat Transfer, with related courses such as Numerical Methods, Electrical Engineering and Control Theory. However, students find it difficult to see how these topics are interconnected and to have a clear view how this knowledge is applied in their working career.

For this reason a new student project (4 credits) was set up on the design of a ground coupled heat pump system for an office building. The process of going through all design steps of this typical engineering job, and hereby relating every step to the corresponding theory, allows to link theory with a real life example and demonstrate how course topics interact. The goal was to use hand methods not requiring specific software, which forced students to program the related equations in a python notebook, instead of just filling in numbers. Defining boundary conditions, calculating heating and cooling load, estimating a load duration curve, defining base and peak load emission systems, designing the hydraulic and aeraulic distribution system layout and sizing a ground coupled heat pump with direct cooling were required steps in order to finalize the design.

This project proved very useful to apply theory touching topics as steady-state and transient heat transfer, heat exchangers, thermodynamic cycles, psychrometry, dynamic system analysis and system simulation. Future courses will add extra focus on heat pump design and pump or fan sizing.

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Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: Thermodynamics; Heat transfer; student project; design; heat pump

1. Introduction

In their 3rd undergraduate year, engineering students of the Faculty of Engineering Technology (KU Leuven, Belgium) have the option to choose a limited amount of credits in course that already specializes towards the future master. This article describes the content of one of these courses that already gives a preview of topics given in graduate course leading to the Master of Energy.

This course, which has 4 credits, wants topics as steady-state and transient heat transfer, heat exchangers, thermodynamic cycles, psychrometry, dynamic system analysis and system simulation to be combined in one design exercise. Moreover, the theory that applies to the different steps in the design process, was not taught in

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separate sessions, but was brought to the students depending on the questions that were raised during the course of the design exercise.

It was chosen to design a heating, cooling and ventilation system for a very simple office building. A ground coupled heat pump system provided the required heating and cooling energy. This system choice ensured that all above mentioned course topics came across while going through all design steps.

The different design steps that students had to take are described in this article, together with examples of their results and some conclusions drawn from their experience.

2. Student design project methodology

The students are required to process all steps a system designer would go through, while developing a full system design:

- Program of requirements
- Determination of nominal heating and cooling power, and load duration curve
- Design of heating and cooling emission system
- Design of heat and cold distribution via water and air
- Design of heat and cold production
- Control

Since design options in all mentioned steps are numerous, in each step choices were made in advance to guide the students in the desired direction

2.1. Tools

It was asked to the students to program their solutions in Python and the Jupyter Notebook [1] as user interface. This interface was chosen because it enables code execution and description of the steps taken in one single file. No other report was expected than their Jupyter Notebook file. Although Python was taught in previous years, and is ideal for this kind of calculations with a lot of iterations, still 1 out of the 6 groups chose to implement all code in Excel and write a separate report.

2.2. Building to be designed

The goal of the project was to design a ground coupled heat pump system and air handling unit for a one-zone office building. Since it was explicitly not the goal to have a building representing full reality, the lay-out was kept very simple:

- Rectangle shaped
- Only one external wall with window
- The other walls are internal walls with neighboring zones at the same temperature
- A flat roof
- The floor separates this zone from an identical zone below
- The building zone is a landscaped office and needs to accommodate 10 occupants
- The fresh air enters the building at zone temperature

Furthermore, it was defined that the building had to be equipped with a double emission system: a base load slow working floor heating/cooling and a peak load fast reacting fan-convactor system. The floor heating system had to provide 80% of the energy to cool or heat the building. Moreover, fresh air had to be supplied by an air handling unit (AHU) equipped with a heat recovery heat exchanger.

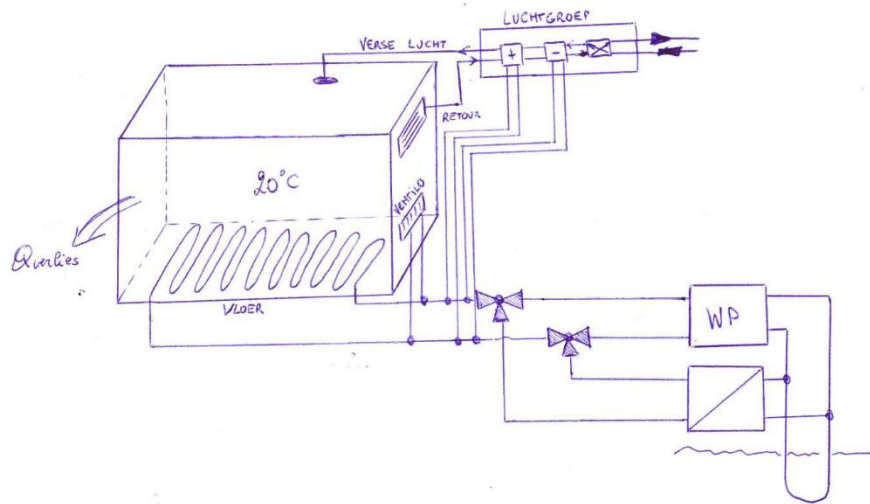


Fig. 1: Schematic view of the building and system to be designed

To keep the design simple, only 1 heat pump and direct cooling heat exchanger was to be designed. They are connected to an close loop borehole system supplying renewable heat and cold to the system. This all led to a schematic view of the building and installation as shown in Fig. 1 (drawn by students).

The choice of this systems incorporates some difficulties that have to be solved during the design:

- Only one temperature level for heating and cooling is available, so the design of floor heating, fan convector and AHU heating and cooling coils has to take this into account
- Heat pump and direct ground cooling deliver respectively low temperature heating (e.g. 35°C) and high temperature cooling (e.g. 15°C). For fan convector and AHU coils these temperatures are different from typical nominal operating temperatures (e.g. 60°C for heating and 6°C for cooling).
- The building to be designed was not balanced in heating and cooling load, so the thermal load on to the ground loops was not in balance.
- The fact that current energy performance regulation had to be followed, led to very well insulated buildings, requiring more cooling that heating.
- The presence of base and peak load system forces to make a choice in installed thermal power for both.

The choice of floor, wall, roof construction and window type was left to the students, but information was given to them about the Flemish Energy Performance regulations [2], defining amongst other requirements, minimum levels of insulation for opaque building constructions and for windows. These descriptions gave inspiration for wall and window definition.

2.3. Program of requirements

The purpose of a building is to create comfortable conditions in order for people to be able to perform their work tasks. Comfort has different aspects, but in this design only thermal comfort and air quality is considered (humidity, light and acoustics are not taken into account).

Students were told to design a class II building with details from EN 15251 (2007) [3]. In this standard they had to find design values for:

- Floor area to be foreseen
- Indoor design temperature

- Required air flows

2.4. Determination of nominal heating and cooling power, and load duration curve

A theory session on heat transfer in buildings was given, reviewing convective, conductive and radiative heat transfer and dealing with combined convective and radiative heat transfer. This led to the definition of operative temperature, encountered in the data of EN 15251. Moreover, it was an introduction to the thermal resistance approach of heat transfer description (overall U-value) for conduction, convection and radiation, which the students encounter in the calculation of the heating and cooling load.

Heating load was to be calculated with EN 12831 [4], while for the cooling load the ‘hand’ method of VDI 2087 [5] had to be applied. The motivation for the choice of this cooling method is the following. Although in their career, students will use software tools to calculate cooling loads, this hand method is an ideal introduction to transient heat transfer in buildings and to approaches encountered in typical building simulation tools:

- The different heat sources in buildings: solar radiation, people, appliances, lighting, ...
- Convective and radiative parts of the heat load
- Time schedules of heat loads and their impact on transient heat load and on the dynamic reacting of the building
- The impact of orientation on the cooling load
- The impact of the thermal mass of the building on the cooling load
- The difference between heating load, with a worst case calculation, and cooling load with transient dynamic approach leading to a daily cooling load profile (Fig. 2)

In general, students encountered no big difficulties in determining the nominal heating and cooling loads, but sometimes it was difficult to judge which of the design options, as offered by the standards, they had to choose for their specific case. Of course, these design options (such as thermal building mass, time schedule, ...) never exactly matches their specific situation.

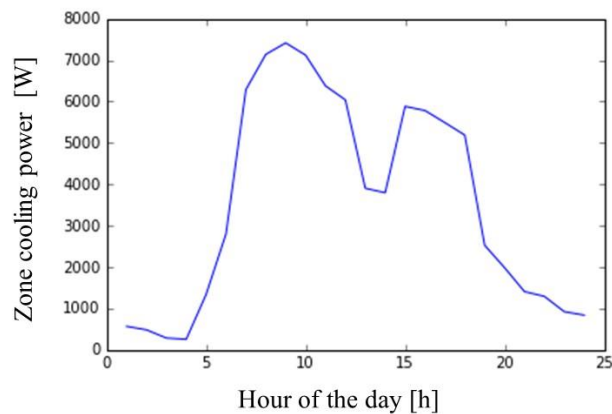


Fig. 2: Result of cooling load calculation for the building zone

Students concluded that the high levels of insulation, as required by the Energy Performance regulation, led to a large unbalance between heating and cooling, with nominal cooling powers being more than 5 times higher than nominal heating powers.

Although no dynamic system simulation was foreseen for this design project, an estimation of the heating and cooling energy of the building zone was asked for. Moreover, this value was required for the design of the borefield of the heat pump. A hands-on method as proposed by the Dutch ISSO81-guideline [6] was proposed to the students. The method correlates heating and cooling powers to the outdoor temperature (and its variation throughout the year).

Students were paid attention to the fact that this is an approximation of reality, because it relates energy use of the building purely to the variation of the outdoor temperature, and that this method does not take into account the effect of solar radiation, thermal mass and control on the final energy use of the building.

Students encountered difficulties in this step since they had to process climate data on temperature and separate office and non-office hours in order to have the correct load duration curve. They had to analyse closely the building time schedules for this. This step came close to what a similar procedure in a dynamic building simulation tool would do.

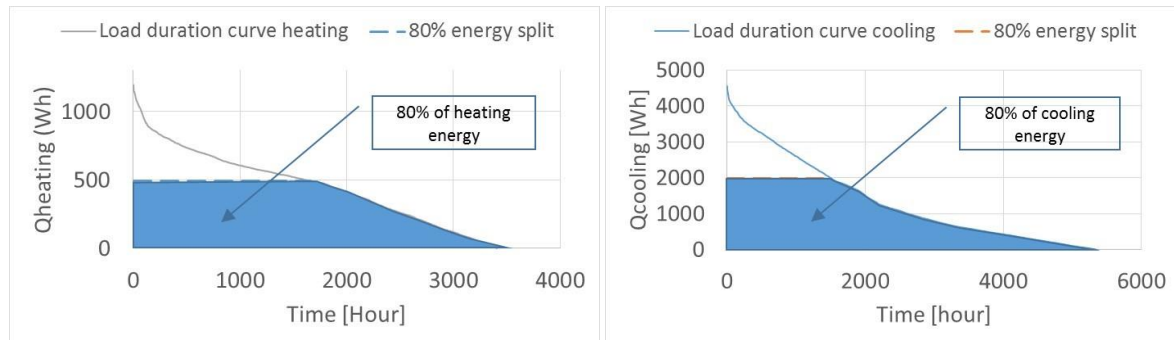


Fig. 3: Load duration curve example for (left) heating and (right) cooling

2.5. Design of heating and cooling emission system

A second important reason for calculating the load duration curve, was the requirement that the floor heating system (acting as base load) had to supply 80% of either heating or cooling energy of the building. This step was introduced into the design exercise in order to show the students that only a relatively small part of the installed thermal power will be used for most part of the time. This shows clearly that part-load behaviour of the heating and cooling system is a very important issue.

Since the area under the load duration curve was used as a representation of the buildings energy use, the student could use this curve to define the design thermal power of floor heating and fan-convectors (the horizontal line in Fig. 3 shows the 80% energy line). Applying this step for both heating and cooling showed that cooling determined the design of both emission systems. An example of one of the results (corresponding to Fig. 3) is shown in Table 1.

Table 1. Designed nominal heating and cooling power of floor heating and fan-convectors.

	Heating (W)	Cooling (W)
Floor heating (80% of energy)	491	1982
Fan-convector (20% of energy)	704	2570

Table 1 clearly shows that, although floor heating is supposed to provide 80% of the required energy, it has to be designed at less than 50% of the nominal building zone power.

An important effect of the choice for on production system for heating (heat pump) and cooling (direct ground heat exchanger) is the fact that only 1 design temperature is available for the different emission systems. Students had to design the floor heating system according to the method defined in EN 1264 [7]. Students were asked to search for catalogue data of fan-convectors and choose an appropriate apparatus to cover the calculated heating and cooling power. This created the problem that they had to apply ϵ -NTU heat exchanger theory to recalculate thermal power data in the catalogue, to their own required situation.

2.6. Design of heat and cold distribution via water and air

Due to time limitations of the course, the design of the water and air distribution system was limited to making up the schematic view of the system (as e.g. shown in Fig. 1). It is the aim to introduce a hydronic software tool in next year's version of the course, in order to correctly design the hydraulic network, including all required valves and connections.

2.7. Design of heat and cold production

The heat recovery with an efficiency of 60%, cooling coil and heating coil of the AHU – no (de)humidification was foreseen – were to be designed with a (h,x)-diagram for moist air. This gave the students the thermal powers required to condition the incoming air to the given indoor temperature set point.

Together with the calculated powers of floor heating and fan-convectors, this led to the sizing of the heat pump and the direct ground heat exchanger used for cooling. The students had to multiply their one-building-zone values with a factor 10-30 in order to achieve realistic values, since they had to look for commercial heat pumps available for their system.

The design of the ground loop system was made using a tool presented in ISSO 73 [8] and put into a web based tool by the Smart Geotherm project [9].

2.8. Control

Design of the control of the system was limited to qualitative description of operational modes of the system.

3. Assignment on transient heat transfer as side project

While calculating cooling load according to VDI 2087 [5], students encountered a method dealing with transient thermal behaviour of materials. After all, the 'S'-factors that are applied in the cooling load method represent the delay that a heat gain encounters before it contributes to a temperature rise in the considered zone. The radiative part of these heat gains is supposed to be first absorbed by the thermal mass of the building before it is transferred by this thermal mass to the zone air as convective heat.

While in the VDI 2087 hand method this transient thermal behaviour is approximated using the 'S' delay factors, building simulation tools apply a dynamic thermal model of the building which is solved numerically to obtain the required building behaviour.

To make students familiar with this transient thermal behaviour, and with the numerical aspect:

- A review theory session is given on transient conductive heat transfer, leading to the lumped capacity representation (RC-networks) for transient conductive heat transfer in solid materials
- The Carslaw and Jaeger [10] analytical solutions for given boundary conditions are presented and discussed

An assignment is given to program and compare the temperature distribution of a solid wall slab (material properties are to be chosen by the students), with a given initial temperature and subject to a temperature step at its boundaries 1 and 2. These situation has been chosen, because the corresponding analytical solution, as given by Carslaw and Jaeger, rather straightforward to implement. The first formula to solve in this assignment is:

$$\rho CV \frac{(T_{w,i+1} - T_{s,i})}{\delta t} = \frac{T_{w,i} - T_1}{R_1} + \frac{T_{w,i} - T_2}{R_2}, \quad (1)$$

which represents the forward differentiated version of the differential equation describing energy balance in the temperature node of the 1st order RCR model,

with timestep δt [s], density ρ [kg/m³], thermal capacity C [J/kgK], volume V [m³], wall temperature T_w [K], surface 1 temperature T_1 [K] ($T_{1,t=0} = 0$; $T_{1,t>0} = T_s = 20$), surface 2 temperature T_2 [K] ($T_{2,t=0} = 0$; $T_{2,t>0} = T_s = 20$), thermal resistance between surface 1 and slab node R_1 [m²K/W], thermal resistance between surface 2 and slab node R_2 [m²K/W].

The second formula to derive the temperature evolution in the slab is an analytical solution, as given by Carslaw and Jaeger:

$$T_w(x, t) = T_s - \frac{4T_s}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} * e^{-k(2n+1)^2 \pi^2 t / 4l^2} * \cos \frac{(2n+1)\pi x}{2l}, \quad (2)$$

with the wall temperature distribution $T_w(x, t)$ [K], surface temperature T_s [K], thermal conductivity k [W/mK], time t [s], position in the slab x [m].

The result of the assignment had to be a graph of the temperature evolution from initial temperature to final steady state temperature for both the analytical solution and the numerical implementation of the RC-network. Furthermore, it was asked to determine the time until steady state was reached, with the analytical solution approach, as well as with the numerical RC-approach. This led to graphs generated by their Python code as presented by students as shown in Fig. 4.

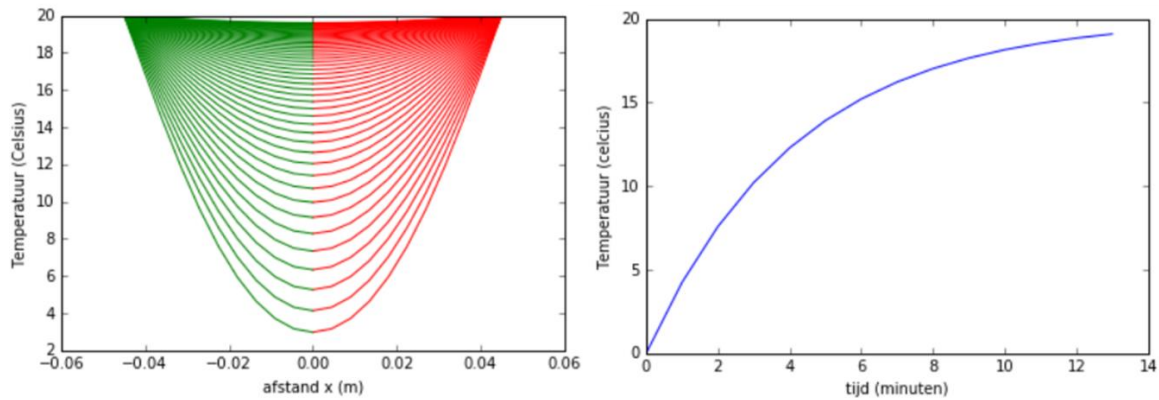


Fig. 4: Temperature distribution as calculated with (left) the analytical solution (x : distance from centre [m]; y : temperature $T_w(x, t)$ [K]) and (right) the numerically solved RCR-model approach (x : time [min]; y : temperature T_w [K])

The analytical solution is found to be difficult to understand and easily subject to errors while implementing this into the Python code. On the other hand, the RC solution required setting up a differential solution procedure, but was still found to be easier to understand.

A corresponding exam question about this assignment assessed if students were aware that an increased number of nodes in their RC-network (e.g. RCRRCR instead of RCR) would bring their numerical RC-solution closer to the analytical solution.

4. Conclusions

This article describes a student project in which they had to design from scratch an office building with a ground coupled heat pump system. The goal of this student project was to set up a design example in which several topics that are treated in different theory courses of the undergraduate engineering curriculum, are combined and in which the interacting of this theory is demonstrated. The chosen building and heat pump system design proved to be an ideal case for this. Heat transfer and thermodynamics were the most important topics applied in this example. It is the aim of future editions of this course to incorporate more topics as fluid dynamics, pump and fan design, frequency control of pump and fan motors, into the design project.

Student appreciated the hands-on approach of the course and the fact that question they encountered were always drawn back to the underlying theory. In this way they learned at first hand how the different theoretical topics interact when applied to an integrated system design.

Acknowledgements

The author kindly acknowledges KU Leuven, Faculty of Engineering Technology (iiw.kuleuven.be) for giving the opportunity to teach young, interested and motivated students. Furthermore, the European Union is acknowledged by funding the Horizon 2020 project GEOTeCH (Grant Agreement No: 656889), from which the inspiration for the student project originates.

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