

A GENERAL PROCEDURE TO MODEL THE EXERGY PERFORMANCE OF HYBRID HVAC SYSTEMS IN BUILDINGS

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ABSTRACT

This paper deals with the modeling of the exergy performance of hybrid HVAC systems in buildings.

The work is initiated for the comparison of different systems for concrete core cooling in buildings. The modeling includes the efficiency of the emission systems as well as the heat losses and need for auxiliary power in the system. The aim is to be able to build up models for arbitrary systems in an Excel sheet with “copy paste” technique. The analysis in this phase is limited to steady state analysis.

INTRODUCTION

In recent years we have seen a growing interest in use of so called low exergy systems for heating and cooling in buildings. Usually this implies systems that emit heating and cooling with a low temperature difference. In order to achieve this, large surfaces are needed for the heat emission and the heat sources are more often integrated in the building structures. Floor heating is a common example. Using low temperature differences opens the possibility to utilize low quality energy sources such as solar heated water, heat pumps, cooling using the ground as a heat sink or waste energy from other processes. In the seventies an airborne system, Termodeck®, for heating and cooling became widely used for office buildings in Sweden. The ventilation air was fed into the building via air coils in concrete floor slabs. Preheating or precooling the air generated heating or cooling via the floor or ceiling surfaces while the air entering the room would be close to room temperature. At night the floor slabs could be cooled with outdoor air creating a cold storage to meet the coming hot day. The system showed at that time a very good energy performance. In the early nineties as recirculation of ventilation air was stopped, a discussion was opened on the health issues using concrete ducts, a booming increase in power needed for cooling together with a falling market for office space in Sweden made the market situation difficult, while the system has found its use in UK and on other markets. The development over the recent years has created a new interest in such systems as an alternative to the so called

Concrete Core Cooling system where water coils normally are placed in concrete floor slabs cast in situ. Normally a water born system needs less auxiliary power to transport heat. If the building is anyhow mechanically ventilated the energy balance is no longer obvious. In a life cycle analysis, other aspects such as water safety, durability etc. have to be regarded.

THE COMPUTER PROGRAM

The program developed is a straightforward, modular Excel calculation sheet. It consists of *nodal points*, Figure 1, left, and *connections*, Figure 1, right, which freely can be combined to represent a mass and heat transfer system. In Figure 2 an example of a possible system configuration is shown. The calculated case is assembled by copy-pasting the defined nodal points and connections in correct order. Figure 3 shows a configuration as shows in the program. The result is iterated with Excel’s inbuilt iteration option.

The nodal points and connections contain equations which describe the properties and the state of the system. To assure the overview of a complex system, a color is assigned to each property, Figures 4 and 5.

Connections

The flowing medium, for heating or cooling, flows through the connections, where heat transfer to a set surrounding occurs. It is possible to define two different surroundings for each connection. If for example an intermediate floor slab with water tubes is modeled, it is possible to take into account the different constructions and surrounding temperatures above and below the water tubes.

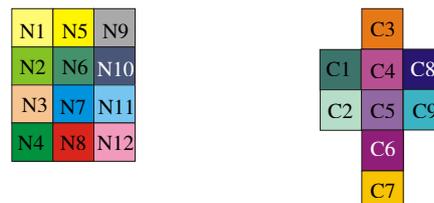


Figure 1. Left a nodal point, right a connection.

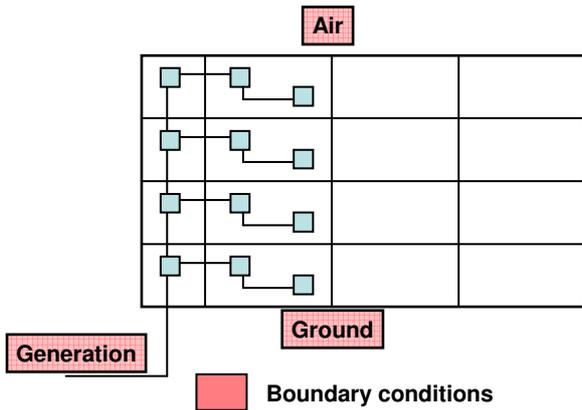


Figure 2. A possible system configuration

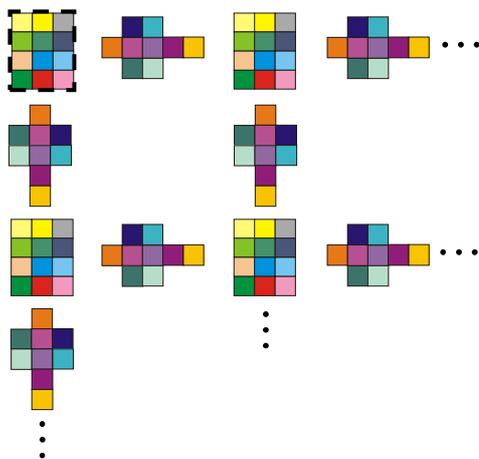


Figure 3. Example of a composition of a system as shown in the program.

C1 Medium spec. heat	C6 Total heat flow
C2 Medium density	C7 Temperature at end of connection (in flow direction)
C3 Massflow	C8 Spec. heat flow S1
C4 Pipe length	C9 Spec. heat flow S2
C5 Floor Area	

Figure 4. Color assignments connection.

N1 Exergy in	N7 Height
N2 Exergy out	N8 Total massflow through the point
N3 Temperature in	N9 System in
N4 Temperature out	N10 System out
N5 Medium in	N11 Pressure out
N6 Medium out	N12 Pressure out

Figure 5. Color assignments nodal point.

Nodal points

At the nodal points the medium temperature and exergy content are calculated and pressure and altitude are defined. Since temperature and exergy content are calculated separately for the medium flowing into the nodal point and for the medium leaving, it is possible to define a nodal point as a system component, e.g. a heat pump or a fan. These components are defined in a list and can be “copy-pasted” into the program. Alternatively the nodal points represent flow mixing or splitting.

The parameters System in/out define the type of construction leading into and from the nodal point. For instance, a distribution pipe leads to the point, a floor slab with water tubes from it.

Equations

The following equations are used for calculating the exergy content E of the medium (Shukuya M., Hammache, A, 2002, Bejan A. et. al. 1996).

$$E = E_{ph} + E_{kin} + E_{pt} \quad (1)$$

$$E_{kin} = \frac{1}{2} \cdot \left(\frac{\dot{m}}{\rho \cdot d_i} \right)^2 \quad (2)$$

$$E_{pt} = g \cdot H \quad (3)$$

Water:

$$E_{ph} = c \cdot \left[(T - T_{ref}) - T_{ref} \cdot \ln\left(\frac{T}{T_{ref}}\right) \right] - \nu(P - P_{ref}) \quad (4)$$

Air:

$$E_{ph} = c_p(T - T_0) - T_0 \left(c_p \ln \frac{T}{T_0} - R \ln \frac{P}{P_0} \right) \quad (5)$$

E_{ph} is the physical exergy, J/kg, E_{kin} is the kinetic exergy, J/kg, E_{pt} is the potential exergy, J/kg, \dot{m} , is the mass flow, kg/s, ρ the medium density, kg/m³, d_i is the inner diameter of the flow coil/duct, m, g is the gravitation constant, m/s², H is the relative height, m, c the specific heat (constant), J/(kg·K), T is the medium temperature, K, T_{ref} the reference temperature, K, ν the specific volume, m³/kg, determined at the temperature T_{ref} , P is the medium pressure, Pa, P_{ref} is the reference pressure, Pa, c_p is the specific heat at constant pressure, J/(kg·K) and R the specific ideal gas constant (J/(kg·K)).

Thermal modeling of hybrid components

The dynamic thermal modelling of hybrid components can be done in the frequency domain.

Examples are shown both in Schmidt D., Jóhannesson G., (2002) and Weber T., Jóhannesson G. (2005). An other example is a combination of a FEM model by Weber T. (2004) and a model developed in MathCad by Karlström P. (2005). The result from the FEM model, the admittances and transmittances for a cross section, are used as input for the MathCad model.

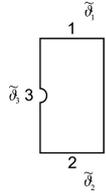


Figure 6. Half cross section of hybrid slab. For symmetry reasons it is enough to model half the coil and half of the distance between the coils.

The following expression derived by Weber et al. (2004b) is utilized to obtain the media temperature along the coil/duct.

$$\tilde{\vartheta}_3(x) = \left(\tilde{\vartheta}_{inlet} - \frac{Tr_{13} \cdot \tilde{\vartheta}_1 + Tr_{23} \cdot \tilde{\vartheta}_2}{A_{c/d} \cdot \rho_{media} \cdot c_{media} \cdot i \cdot \omega - Y_3} \right) \cdot e^{\frac{A_{c/d} \cdot \rho_{media} \cdot c_{media} \cdot i \cdot \omega + Y_3}{A_{c/d} \cdot \rho_{media} \cdot c_{media}} \cdot x} + \frac{Tr_{13} \cdot \tilde{\vartheta}_1 + Tr_{23} \cdot \tilde{\vartheta}_2}{A_{c/d} \cdot \rho_{media} \cdot c_{media} \cdot i \cdot \omega - Y_3} \quad (6)$$

where $\tilde{\vartheta}_3(x)$ is the frequency dependent temperature along the coil/duct, $\tilde{\vartheta}_{inlet}$ the inlet temperature, $\tilde{\vartheta}_1$ and $\tilde{\vartheta}_2$ the surrounding air temperatures on each side of the slab, Tr_{ij} the transmittance from point i to j , Y_3 the admittance in point 3, ω the angular frequency, $A_{c/d}$ the coil/duct cross section area, ρ_{media} the media density and c_{media} the specific heat for the media. To obtain the heat flow distribution along the coil/duct, equation 3 is solved (Weber et al. 2004b)

$$\begin{pmatrix} \tilde{q}_1(x) \\ \tilde{q}_2(x) \\ \tilde{q}_3(x) \end{pmatrix} = \begin{pmatrix} Y_1 & Tr_{21} & Tr_{31} \\ Tr_{12} & Y_2 & Tr_{32} \\ Tr_{13} & Tr_{23} & Y_3 \end{pmatrix} \begin{pmatrix} \tilde{\vartheta}_1 \\ \tilde{\vartheta}_2 \\ \tilde{\vartheta}_3(x) \end{pmatrix} \quad (7)$$

with definitions according to equation 2 and numbering according to Figure 6.

The average surface temperatures on the surfaces towards the room along the coil/duct are calculated with the following equations (7) where α is the surface heat transfer coefficient, W/m^2K . A more detailed temperature distribution along the surface can be derived from the nodal temperatures for the cross sectional FEM solution.

$$\tilde{\vartheta}_{s1}(x) = \tilde{\vartheta}_1 - \frac{\tilde{q}_1(x)}{\alpha} \quad \tilde{\vartheta}_{s2}(x) = \tilde{\vartheta}_2 - \frac{\tilde{q}_2(x)}{\alpha} \quad (8)$$

CONCLUSIONS

The work has lead to a procedure to investigate the overall exergy of HVAC systems in buildings, modeling in a flexible way that can easily be accessed by the practicing engineer. A general statement on the feasibility of an air born versus waterborne system can not be made. This will be depending on other factors such as the required air exchange rate and the heating and cooling loads. For both system types the recipe of success is to keep the loads for heating and cooling under certain limits.

The systematic approach for the definition of the actual system allows for a flexible way to build up a system or a set of systems and the built in solver in the Excel worksheet swiftly brings about an iterative solution for systems with closed feedback loops.

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