Modelling the Use of Exhaust Air Heat Recovery Coils Coupled with Heat Recovery Chillers

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Abstract

One increasingly common design feature is the use of a hydronic coil in the exhaust air stream for the purpose of recovering heat in systems that use heat recovery chillers. The feature is a desirable alternative to plate or rotary exhaust air heat recovery as it allows for the recovered heat to be used for multiple purposes, such as heating, terminal reheat, preheating domestic hot water or other building heating demands. In comparison, conventional exhaust air heat recovery is limited to system supply air heating only.

However, the most commonly used whole building energy modelling software programs in industry do not directly allow for the modelling of a hydronic coil in an exhaust air stream. In this paper, two methods of modelling exhaust air heat recovery are described. A custom control method in EnergyPlus to directly model a coil in the exhaust air stream is contrasted with a simplified workaround that could be integrated with any major software package.

1 Introduction

Exhaust air heat recovery in general is a widely understood design feature, and can provide significant energy savings for buildings that employ it. Established simulation methods exist for heat exchanger and heat wheel applications, however, the exhaust air heat recovery system described in this paper is a novel approach and existing heat recovery modelling methods cannot be applied. Typical exhaust air heat recovery applications use building exhaust air through a heat exchanger to directly warm entering building ventilation air. The system described in this paper brings building heat from the exhaust air into the central plant via a water-to-water heat pump or heat recovery chiller, allowing exhaust air heat to be usefully applied to any heating application in the building, even when the entering ventilation air does not require heat.

One scenario where an exhaust air heat recovery coil coupled with a heat recovery chiller might be advantageous over a traditional exhaust air heat recovery device is in the case of a typical recirculating air system with 30% outdoor air. The system would typically have a supply air temperature setpoint of between 13°C and 18°C with a return air temperature in the range of at 22°C to 25°C. In this case, the outdoor air temperature would need to be below -4°C to -8°C in order for a traditional heat recovery device to provide any useful heat. There may be other heating demands in the building at an outdoor air temperature well above -4°C; however, the exhaust air heat cannot be usefully recovered as it is not needed at the system level. The system described in this paper would allow that heat to be taken from the exhaust air stream and used to deliver heating where it is needed.

The main disadvantage to this exhaust air coil to heat recovery chiller method of heat recovery is that the chiller requires an input of electricity. Energy cost considerations may also affect the viability of this strategy in a particular situation; however, energy costs are not discussed in this paper.

This design feature is becoming increasingly common; however, it cannot readily be modeled in any of the most commonly used simulation software in industry. This paper will describe two methods for modelling an exhaust air coil heat recovery system, one a post-processing method that can be applied to any simulation software, and the other an EnergyPlus specific method using an Energy Management System (EMS) program. The physical characteristics of hydronic coils in an exhaust air heat recovery application will also be discussed, in the context of applying these characteristics in building energy simulation.

This paper is the first part of a more detailed investigation that will explore this design feature in detail. The current paper describes two modelling methods and compares the assumptions made in each method. Future work will test and compare the results obtained between methods as well as with measured operational data.

System Description

The exhaust air heat recovery coil system under consideration consists of a hydronic coil in an exhaust air stream, which is controlled to provide additional heat to a heat recovery chiller system when heat recovery is desired. The hydronic coil in question is on the chilled water loop of the building. The coil draws heat from the exhaust air stream into the chilled water stream, which then returns to a chiller with that additional heat. The additional heat in the chiller return water requires the chiller to do additional work to cool that water back to the chilled water supply setpoint. The additional work done by the chiller allows more heat to be recovered to the hot water loop, which can then be distributed by the plant to handle heating loads. In this way, a load is placed on the chilled water loop to satisfy a call for heating.

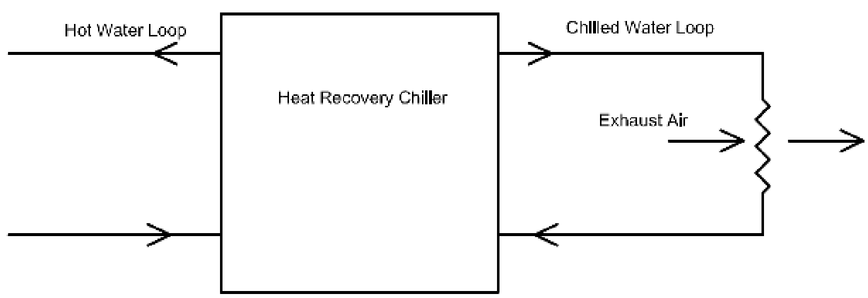

Figure 1. Heat recovery system schematic

Heat recovery chiller run time is increased, providing additional heat to the building, reducing the use of less-efficient boilers.

Physical Characteristics of Cooling Coils

In order to understand the assumptions and approximations made about exhaust air coils in the modelling methods described, we will first discuss the physical real-world characteristics and expected behaviour of hydronic coils in an exhaust air heat recovery application, then examine the assumptions in both the simplified post-processing method and advanced software method, and the ways in which these two modelling methods differ. The hydronic coils considered in this application cool the exhaust air stream, so can be considered as cooling coils, though the goal in this case is to cause the heat recovery chiller to perform additional work by adding heat to the chilled water loop, rather than to cool or dehumidify the air to maintain space comfort.

Hydronic cooling coils can be characterized and described in a number of different ways, and a great deal of information on selection, design, performance, and simulation is available. In order to examine simulation methods for hydronic coils in an exhaust air stream for chiller heat recovery, we will focus on those aspects that may have a significant impact in simulating the exhaust air coil application.

For a space conditioning application, cooling coils would be selected for comfort based on sensible and latent heat removal requirements (ASHRAE, 2004.) Manufacturers provide tables of sensible and latent heat removal capacities at various operating conditions to aid in selection. In the current application, space comfort is not a concern, nor is the ratio of latent heat to sensible heat removed. Either mode of heat removal from the air will transfer heat into the coil and from there to the heat recovery chiller, fulfilling the goal of increasing the temperature of the liquid inside the coil.

Cooling coils do not have a minimum part load cutoff below which they cannot function, though their performance is reduced. Hydronic cooling coils can be controlled by changing the air flow or by changing the water flow. Typically, the air flow through the coil would be changed using either face and bypass dampers, or by using a variable speed fan. The water flow can be changed using a valve or variable speed pump (ASHRAE, 2004.) In the case of exhaust air coils, the exhaust air flow rate is required by the system; therefore coil capacity must be controlled through the water flow.

Cooling coil capacity is dependent on a number of characteristics, including the tube and fin material, coil arrangement and circuiting, tube and fin dimensions and shapes, as well as the flow rates of air and water and the temperature differential between the two fluids (Paranjpey, 2003.) Maximizing both contact and temperature differential maximizes the coil capacity. Most factors in coil capacity are constant at any part load condition (e.g. the fin shape remains constant), however, changes in operating conditions can have an effect on several heat transfer characteristics. Naturally, controlling the coil by altering the air or water flow rate will alter the coil's current capacity directly due to the lower mass flow rates. However, operation at part load does also lead to a decrease in overall heat transfer coefficient (Paranjpey, 2003.) The sensible heat ratio is also affected significantly by part-load operation (Sekhar & Tan, 2008.) However, in an exhaust air heat recovery application, the changing ratio of sensible and latent heat removed by the coil is not a concern, since either will transfer heat into the plant loop.

2 Simplified Post-processing Method

Given that simulation software does not currently have the capability of directly modelling a hydronic coil as a way of indirectly providing heat through a chiller heat recovery system, there is a need in industry for an effective and efficient method to analyze the energy impacts of this system. The simplified method described here is meant to be generally consistent with level of effort and accuracy used for energy simulation applications in industry, such as design assistance, code compliance and green rating systems.

A method that can be applied to any simulation software using hourly results must consider several factors that characterize the performance of a hydronic exhaust air heat recovery coil. The heating load and system controls determine the call on the exhaust air coil; the exhaust air flow, exhaust air temperature, and coil capacity determine the amount of heat that can be taken from the exhaust air; and heat recovery chiller characteristics determine how efficiently and in what quantity that heat can be provided to the space heating system.

A simple post-processing method to account for exhaust air hydronic heat recovery can be summarized in the following steps:

1) Determine the heating demand on the plant,

2) Determine the heat available from the exhaust air stream based on the mass flow and temperature difference of both the exhaust air stream and chilled water coil,

3) Limit the heat recovered based on the demand on the plant, the maximum capacity of the air stream, the nominal capacity of the coil, and the heat recovery capacity of the chiller, and

4) Determine additional power input into the chiller based on additional load determined from step 3, using chiller performance characteristics.

This method makes a number of approximations; we will consider these assumptions, as well as summarizing the methods used in EnergyPlus simulation software to compare advanced software hydronic coil simulation practice with the simplified workaround method.

The simplified post-processing method assumes that the coil is capable of transferring all heat available to it under any conditions (i.e. no consideration is made for part load operation of the coil), neglects changes in the enthalpy of the air (i.e. temperature drop only), and ignores the effects of the coil on plant loop temperatures in the determination of chiller COP, and ignores the effects of changing the coil flow rate on pump power.

Treatment of Hydronic Coils in the Simplified Post-Processing Method

In the simplified post-processing method, the nominal capacity of the coil used is that provided by the designer.

Based on the nominal exhaust air heat recovery capacity and exhaust air flow rate, the design temperature drop of the exhaust air stream across the coil can be calculated. A reduction in air stream capacity can then be modeled when the exhaust air temperature is not capable of providing a sufficient temperature drop, or when the exhaust air flow rate is lower than the design rate. This method of reducing the capacity based on exhaust air temperature takes into account only the sensible heat content of the air stream, and neglects the latent heat content. While the exhaust air coil application does not have a comfort-based sensible heat ratio it is required to condition to, the latent heat in the air stream may significantly increase the capacity of the exhaust air coil, and therefore increase the capacity of the system to provide heat recovery.

The reduction of capacity at part load based on flow rate of exhaust air is modeled as a linear relationship between mass flow rate of the air or temperature change across the coil and heat content of the air stream. This capacity reduction calculation takes into account only the characteristics of the air, rather than the combined behaviour of the air and water, as mediated by the coil.

Refining the Treatment of Hydronic Coils in the Simplified Post-Processing Method

Different circumstances may call for different levels of detail and different areas of focus. The recommendations below offer options for increasing the accuracy of the simplified post-processing method based on the physical characteristics and advanced simulation methods discussed.

The heat content of the air should ideally be determined based on enthalpy content. Under some circumstances this may be a negligible difference with using temperature, in particular if the temperature drop was calculated based on a known coil capacity (i.e. design and operation conditions are all assuming sensible cooling only,) and the expected water content of the air is not expected to be a strong function of exhaust air temperature.

The heat transfer capacity of the coil is dependent on several factors, notably the mass flow rates and temperatures of water and air (Wetter, 1999.) The part load performance characteristics of the coil are neglected in the simplified post-processing method described. It would be possible to incorporate the part load characteristics following the same algorithm as described in the Exhaust Air Coil EMS Subroutine below; however, the use of an iterative calculation within a post-processing method is onerous and not likely to be frequently implemented.

Heat Recovery Chiller in Post-Processing

In the simplified post-processing method, a chiller COP and a compressor power must be applied to the heating load handled by the heat recovery chiller. One option for this is to assume a constant compressor power and to apply a constant seasonal COP. A more accurate method would incorporate performance curves as a function of hourly part load ratio and return chilled water temperatures to adjust the COP, and consequently, compressor power. However, since the post-processing method does not incorporate the effects of the coil into the chiller loop temperature drop, the use of a temperature curve adjustment would introduce some inaccuracy into any calculation when the chilled water loop is not at its design temperature.

3 EnergyPlus Modelling Method

Treatment of Hydronic Coils in EnergyPlus Simulation

EnergyPlus allows detailed input of cooling coil geometry and characteristics, but also has the ability to use simplified capacity and mass flow rate inputs to calculate the heat transfer, UA (the product of the heat transfer coefficient, U, and the face area of the coil, A). It also provides two options for simulation method; simple or detailed. The simple analysis mode operates the coils as either wet or dry, whereas the detailed analysis mode simulates the coil as partially wet and partially dry (EnergyPlus, 2013b.) The simple analysis is the default and is typical for annual building energy simulations, while the detailed mode can be used for more focused studies.

The UA is a combined factor based on the equation

$$Q = U \cdot A \cdot \Delta T \quad (1)$$

Where:

Q = Coil cooling capacity (W)

U = Overall coil heat transfer coefficient ($W/m^2 °C$)

A = Coil surface area (m^2)

ΔT = Temperature difference between coil inlet water and air (°C)

Under the simple simulation method in EnergyPlus, the fully dry calculation states that (1) the sensible load is equal to the total load, and that (2) the humidity ratio of air entering the coil is equal to the humidity ratio of air leaving the coil. Then the total load is simply the capacity of the air stream multiplied by the change in air temperature across the coil. In contrast, the fully wet operation uses an enthalpy based calculation.

EnergyPlus re-calculates the UA at every timestep as a power function of the mass flow rates and inlet temperatures of air and water. This leads to a non-linear capacity reduction based on the interaction of the water and air temperatures and mass flow rates, as well as coefficients based on coil characteristics. This UA calculation method assumes no condensation.

The Need for an EMS Program

A potential method for modelling exhaust air coils would be to use the EnergyPlus Energy Management System (EMS) feature, where the user can create custom programs and controls within an EnergyPlus model.

A custom control scheme is required because a coil is always a demand component from the perspective of the plant (EnergyPlus, 2013a, pp. 50); in other words, it places a demand on the plant to condition the air stream, but it cannot be used as a plant supply component to allow the plant to meet the demands of other components. A custom control scheme using an Energy Management System program allows the coil to be controlled to meet loads.

The EMS feature allows a user to essentially code their own custom extensions of EnergyPlus within an energy model, allowing custom programs and controls to be used. This code is written in an EnergyPlus specific language, and can use variables and functions from elsewhere in the model. EnergyPlus will execute that code in conjunction with running the rest of the simulation. An EMS program that could be used to extend EnergyPlus functionality to enable modelling of an exhaust air coil system is described here.

This EMS program is described in detail below; however it has not been fully developed and tested within EnergyPlus at this time.

The EMS program must perform three tasks:

1) Find the change in chilled water flow necessary to allow the heat recovery chiller to meet the heating demand on the plant,

2) Check that both the chiller and coil are capable of delivering the desired heat transfer at current operating conditions, and

3) Take action to control the coil.

EMS Program Structure

The EMS capability in EnergyPlus is dependent upon the use of forward prediction. EMS does not have the ability to request an additional iteration from EnergyPlus, so cannot try a value, test the result with the rest of the model, and take an action depending on that result. EMS programs can iterate within the EMS subroutine itself (so, for example, a 'while' block could be included in an EMS program), but cannot incorporate interactions with other modules except as inputs at a single operational state and outputs at a single operational state for each EnergyPlus iteration. Therefore, it is not possible to simply try a value for coil water mass flow rate, see how much heat recovery it provides, then try another value until the heating load is met by the heat recovery system. A method for calculating the anticipated response of EnergyPlus to a certain coil mass flow rate must be developed within the EMS program.

The EMS program requires a number of sensors, which receive input from elsewhere in the EnergyPlus simulation. The program requires sensors for heating demand rate on the heat recovery chiller, the chiller part load ratio, chilled water mass flow rate, chilled water leaving temperature, condenser leaving temperature, and exhaust air coil inlet temperature and mass flow rate.

An actuator is the element that causes a change to the simulation. A single actuator is required; controlling the water mass flow rate of the exhaust air coil to cause the heat recovery chiller to meet heating loads.

An EMS program may be called at various points within the simulation process; because the current program is intended to interact with and influence HVAC systems, it is called inside of the HVAC system iteration loop.

The program is divided into two subroutines that run in sequence, the first handling calculations related to the chiller and the second handling calculations related to the exhaust air coil.

Chiller EMS Subroutine

This subroutine calculates what change in mass flow rate to the chilled water loop is needed to get the heat recovery desired from the chiller. Detailed calculations have not been provided; equations can be found in the EnergyPlus Engineering Reference (2013.)

The goal is to run the chiller at the exact capacity to provide a heat rejection amount equal to the plant heating load. The subroutine calculates the current evaporator cooling required to meet the sensed value for the heating demand rate on the plant. The heat rejection available from the chiller is a function of current evaporator cooling and incorporates the compressor power and false loading heat. Compressor power and false loading are functions of part load ratio, which is itself a function of reference cooling power (a known value that remains constant through the simulation) and current evaporator cooling (EnergyPlus, 2013b, p. 1041-1048.) The calculation then consists of a series of equations with only one unknown, which can be solved for evaporator cooling rate.

The subroutine must also check that the heating the EMS attempts to provide stays within chiller capacity limits. Chiller reference capacity must be modified for current operating conditions using the current chilled water leaving temperature and current condenser entering or leaving temperature, all of which are known from sensors. The evaporator capacity as a function of temperature curve is evaluated (this curve is a typical EnergyPlus input already included in the model), and the full load cooling capacity of the chiller at current operating conditions is found from the curve value and evaporator capacity at reference conditions (known from the chiller object input). If the chiller capacity is insufficient to provide all of the heat recovery, the evaporator cooling requested by the subroutine must be re-set down to the chiller capacity at the current conditions.

Knowing the evaporator cooling that is needed to provide the correct heat recovery rate (or the maximum evaporator cooling available), the chilled water mass flow rate required to place that load on the chiller must be found. The evaporator cooling rate can be defined as a function of chilled water mass flow available, the specific heat of chilled water, and the change in water temperature across the chiller (EnergyPlus, 2013b, p. 1043.) Using sensor values for specific heat and chilled water entering and leaving temperatures, the desired chilled water mass flow rate is calculated.

Exhaust Air Coil EMS Subroutine

This subroutine checks that the coil has sufficient capacity to remain at a constant leaving water temperature at the mass flow rate called for from the coil under the current operating conditions. The UA of the coil can be calculated as a function of coil inlet water and air temperature and mass flow (Wetter, 1999), which are known values (using the desired coil mass flow rate.) With UA known for the desired condition, the coil capacity is dependent on enthalpy drop of air across the coil and on water outlet temperature. The air outlet enthalpy is calculated based on the heat transfer rate desired from the coil, and checked against some reasonable minimum value of outlet enthalpy. If outlet enthalpy is acceptable, the coil provides the water mass flow rate requested. If the coil air outlet enthalpy is lower than the minimum, coil mass flow is re-set lower incrementally or through a false position method, with UA recalculated and minimum air outlet enthalpy re-checked against the minimum, until the coil capacity and mass flow rate converge.

The water mass flow rate in the exhaust air hydronic coil can now be controlled using the coil actuator to provide the required heat recovery from the chiller.

4 Discussion

The chiller EMS subroutine described has several advantages over the post-processing method. The simplified post-processing method would typically use hourly results from the simulation program as an input, however, system iteration frequency may in fact be more than hourly. The EMS program is called inside the system iteration in EnergyPlus, which has a timestep between 1 and 15 minutes, depending on how rapidly space conditions are changing. Hourly results represent an average or sum of these iterations.

A second advantage to the EMS method is that it integrates with other aspects of the model. This is expected to affect the modeled pumping power, as the mass flow rate through the loop changes due to changes in the coil mass flow rate. Additionally, the pump maximum flow rate may be a limiting factor in available heat recovery, as maximum mass flow rate through the pump would limit the mass flow rate through the coil. The flow rate through other demand components on the loop could also limit the water mass flow rate available to the coil, thereby limiting available heat recovery. These factors require interaction with other components of the model, and cannot be modeled using the post-processing method.

Finally, the EMS method re-calculates the coil heat transfer coefficient to limit coil capacity based on changing operating conditions. This uses an iterative method that is onerous to implement in the post-processing method and is not likely to see widespread adoption.

A major assumption in the EMS method is the use of a fixed minimum outlet air enthalpy.

In order to select an appropriate modelling method given the lack of a direct function in the most commonly used modelling software packages in industry, the assumptions in the methods presented must be understood, and the advantages and disadvantages of each method considered. Future work will test and compare energy simulation results using each of these methods, as well as comparing with measured operational data.

The simplified post-processing method presented can be refined to include air stream enthalpy (rather than sensible-only) operation, as well as accounting for changes to heat transfer effectiveness based on operating conditions. Chiller efficiency and compressor heat can be calculated hourly as functions of operating temperature and part load operation.

The EMS program within EnergyPlus includes the effects of part load operation and operating temperatures on the coil and chiller, but also provides the opportunity for the exhaust air heat recovery coil system to interact with other HVAC modules. This is expected to affect pumping power, as the mass flow rate of the chilled water loop is altered based on mass flow requested by the coil. Pump and loop flow may also prove limiting factors on available heat recovery capacity, if mass flow rates requested cannot be met.

5 Conclusions

A post-processing method to characterize the performance of hydronic exhaust air heat recovery coils has been described, and several possible refinements proposed. Using enthalpy based calculations for hydronic coil heat transfer, as well as updating the overall coil heat transfer effectiveness with each timestep, would increase the accuracy of the method. Additionally, the use of hourly rather than seasonal chiller performance characteristics (efficiency and compressor power) is recommended.

An EnergyPlus Energy Management System program has been described, showing a method for modelling hydronic exhaust air coils within the EnergyPlus. This method includes additional refinements beyond those deemed feasible for the post-processing method, as well as having the ability to affect other HVAC system modules, such as by requesting loop flow and thereby affecting pump power.

The post-processing method can be implemented with any simulation software, while the EnergyPlus Energy Management System program can be implemented in EnergyPlus and may act as a basis for future integration of exhaust air hydronic heat recovery coils into simulation software.

Future work will test both methods and compare results between methods as well as with measured operational data. The authors are involved in projects with a hydronic coil coupled with heat recovery chiller system that incorporate extensive measurement systems, where data will be downloaded and compared against simulations performed using both methods.

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