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Global optimization of the production and the distribution system for typical European HVAC systems

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Abstract

European countries have agreed on a new 2030 Framework with a 30% improvement in energy efficiency compared to projection and a 40% cut in greenhouse gas emissions compared to 1990 levels. With an estimated 11% of all the electrical energy used in Europe consumed by HVAC systems, the improvement of their efficiency is a key element to reach these targets. When looking at the energy flow in typical European HVAC systems, one can observe important degradation in efficiency associated to heating and cooling energy transportation systems together with a non-optimal use of the production plant. These inefficiencies are direct consequences of the system design with, quite often, a lack of consideration of the system part load or its off-design operation. This research attempts to identify the sensitivity of both cooling and heating HVAC systems to these conditions and to propose an approach to optimize the design and the operation of HVAC systems integrated in buildings considering trade-off between primary systems efficiency, distribution losses and auxiliaries consumption.

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Keywords: HVAC system; Optimization; Sensitivity analysis; Part load; Off-design operation; Distribution system

1. Introduction

The IEA project Annex 59[1] aims to improve current HVAC systems, by examining how to achieve high temperature cooling and low temperature heating by reducing temperature differences in heat transfer and energy transport process. When looking at the energy flow in typical European HVAC systems, one can observe important losses associated to

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heating and cooling energy transportation and a non-optimal use of the associated production plant, leading to significant reduction of their performance. To date, little research has focused on the optimization of HVAC systems from a building integration perspective.

Nomenclature

$\dot{M}_{w,boiler}$	Water flow rate in the boiler [kg/s]
$\dot{M}_{w,ev}$	Water flow rate in the evaporator [kg/s]
$\dot{M}_{w,ev,n}$	Nominal water flow rate in the evaporator [kg/s]
VFR	Volume flow ratio [-]
$T_{a,cd,su}$	Condenser supply air temperature [°C]
$T_{w,boiler,su}$	Boiler supply water temperature [°C]
$T_{w,boiler,ex}$	Boiler exhaust water temperature [°C]
$T_{w,ev,ex}$	Evaporator exhaust water temperature [°C]

In most European country HVAC system design procedure, the focus is made on satisfying the nominal design conditions for heating and cooling system. The procedure usually starts with the determination of the internal and external loads, together with hygienic criteria, to calculate the corresponding sensible and latent heating and cooling demands. The evaluation of these loads is typically defined in EN or national standards/methods. The second step consists in the selection of the type of secondary system to integrate into the building and the calculation of its cooling and heating capacity.). The selection and sizing of the heat sources and heat sinks are then the third and often the last step of the design procedure and is based on available types of energy sources/sinks. The total installed power of the primary systems comprises the nominal installed power of the previously selected systems (terminal units and AHU components) and the evaluated nominal heat losses in the supply pipes (often a percentage of usable installed power with a typical maximum value of 5%).

In this procedure, the evaluation of the performance of the system operating at part load or in off-design conditions and its optimization are not considered. This paper investigates the influence of such conditions on cooling and heating primary system performance. A sensitivity analysis is performed for an air-condensed chiller and a condensing boiler, two widely used systems in European buildings. The integration of these systems into the buildings is also discussed in the second part of the paper. The difficulties but also the possibilities of global optimization are presented.

2. Sensitivity analysis of typical European primary HVAC systems

2.1. Heat sink : Air-Condensed Chiller

The first part of the study focuses on the sensitivity of the primary HVAC system to part load or off-design operation. As a starting point, a typical European chilled water production system, the air-cooled liquid chiller, is selected and analyzed using a semi-empirical model[2] validated on manufacturer data. The selected chiller is an air-cooled screw compressors chiller. Its operating range and the nominal conditions considered for the sensitivity analysis are presented in Table 1.

Table 1. Chiller operating range and nominal conditions

	Unit	Minimum	Maximum	Nominal
Evaporator water supply temperature – $T_{w,ev,su}$	°C	6.8	21	12
Evaporator water exhaust temperature – $T_{w,ev,ex}$	°C	3.3	15	7
Condenser air supply temperature – $T_{a,cd,su}$	°C	-10	55	30
Evaporator water flow rate – $\dot{M}_{w,ev}$	kg/s	5.3	34.1	19.44

Fig. 1 presents the sensitivity of the chiller efficiency to $T_{w,ev,ex}$ for different $T_{a,cd,su}$ considering PLR = 1 (the load at the evaporator is the nominal load), $\dot{M}_{w,ev} = \dot{M}_{w,ev,n}$ and $\Delta T_{w,ev}$ = 5K (Fig. 1.a), PLR = 0.3 (the load at the evaporator is 30% of its nominal load), $\dot{M}_{w,ev} = \dot{M}_{w,ev,n}$ and $\Delta T_{w,ev}$ = 5K (Fig. 1.b). It shows the important influence of $T_{w,ev,ex}$ on the chiller efficiency with, for an increase of 1K of the $T_{w,ev,ex}$, an increase in EER from 2.4% and 2.8% at PLR=1 and from 2.0% and 2.2% at PLR=0.3. It means that if an outside temperature of 25°C is considered as example, the chiller EER can increase from 3.85 to 4.36 at PLR=1 by increasing the $T_{w,ev,ex}$ from 7°C to 12°C which would lead to a 13% improvement of efficiency of the system. Comparing Fig. 1a and Fig. 1b, one can see the chiller performance are decreased at part load conditions (at PLR = 0.3). From the chiller point of view, the introduction of high temperature cooling is clearly beneficial. However, these increase of water temperature will have an impact on the sizing of the secondary system leading to an increase of auxiliaries consumption (due to additional pressure drop in the hydraulic system and probably also on the air-side for the AHU). In Fig. 2, the sensitivity of the chiller efficiency to evaporator water flow rate is presented considering the same conditions as in Fig. 1 but with water flow rate equal to 50% of the previously considered nominal water flow rate. The impact of a reduction of the water flow rate (leading to an increase of the ΔT between supply and exhaust water temperature in the evaporator), is lower than the impact of $T_{w,ev,ex}$. One can observe an average decrease in EER of 0.65% PLR=1 and of 0.41% at PLR=0.3. It is also worth noting that the chilled water flow rate could be considered as a sensible parameter in the optimization procedure for the cooling system since its impact on the chiller efficiency is low while its impact on the system performance can be high with its direct and indirect influence on the auxiliary's consumption.

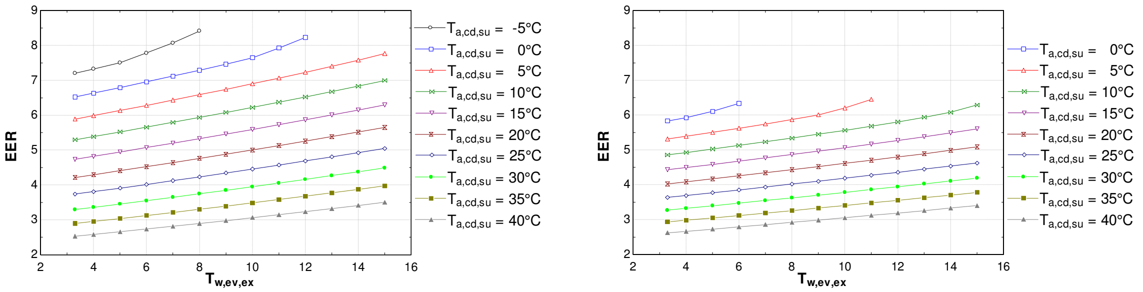

Fig. 1. Sensitivity of the air-cooled chiller efficiency to evaporator exhaust water temperature for different condenser supply air temperature at: (a) PLR = 1 (for $\dot{M}_{w,ev} = \dot{M}_{w,ev,n}$ and $\Delta T_{w,ev}$ = 5°C) , (b) PLR = 0.3 (for $\dot{M}_{w,ev} = \dot{M}_{w,ev,n}$ and $\Delta T_{w,ev}$ = 1.5°C)

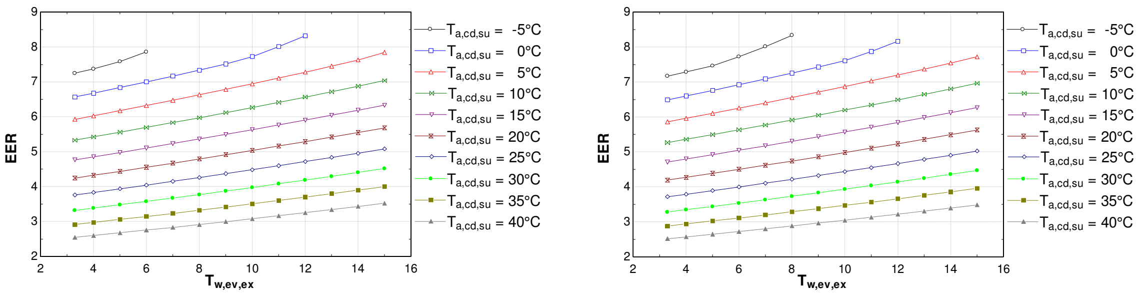

Fig. 2. Sensitivity of the air-cooled chiller efficiency to evaporator exhaust fluid temperature for different condenser supply air temperature at: (a) PLR = 1 (for $\dot{M}_{w,ev} = 0.5 \cdot \dot{M}_{w,ev,n}$ and $\Delta T_{w,ev}$ = 10°C) , (b) PLR = 1 (for $\dot{M}_{w,ev} = \dot{M}_{w,ev,max}$ and $\Delta T_{w,ev}$ = 1.85°C)

2.2. Heat source : Gas Condensing Boiler

In non-residential European buildings, one of the most commonly used heat source is still the boiler. A sensitivity analysis of a gas-condensing boiler is presented using a simplified boiler model[3] based on manufacturer data. The variables considered for the boiler sensitivity analysis are the boiler supply water temperature $T_{w,boiler,su}$, the boiler exhaust water temperature $T_{w,boiler,ex}$, the part load ratio PLR and the volume flow ratio VFR (defined as the ratio between the actual water volume flow rate and the nominal water volume flow rate in the boiler).The first results are presented in Fig. 3 with the sensitivity of the condensing boiler efficiency to $T_{w,boiler,su}$ for different $T_{w,boiler,ex}$ at full load (Fig. 3.a) and at 30% PLR (Fig. 3.b), From Fig. 3, it can be concluded that the lower the return temperature is, the more efficient the boiler is (since more latent heat is recovered in the boiler fumes). The influence of the boiler exhaust water temperature (usually the setpoint) is also noticeable but with a much smaller impact. At first, when analyzing these results for the boiler, one can considered that the optimal point of operation should be chosen to achieve not only the lowest boiler supply water temperature but also the lowest boiler water exhaust temperature. However, in the perspective of the system integration, it is interesting to look into a third direction with the sensitivity of the condensing boiler efficiency to VFR for different $T_{w,boiler,su}$ at full load (Fig. 4.a) and at 30% PLR (Fig. 4.b).

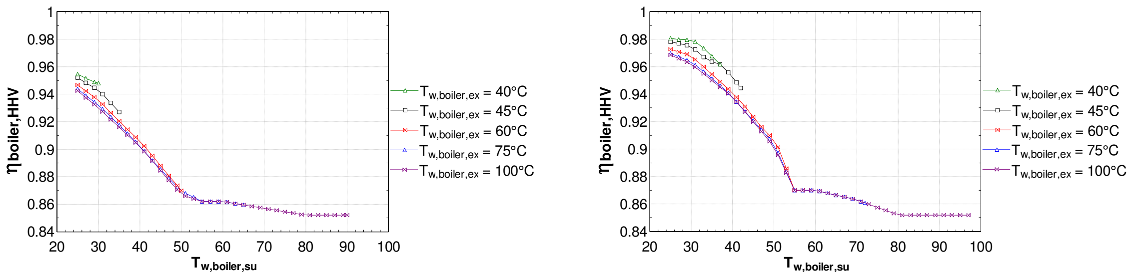

Fig. 3. Sensitivity of the gas condensing boiler efficiency to supply water temperature for different exhaust water temperature setpoint: (a) at PLR = 1, (b) at PLR = 0.3.

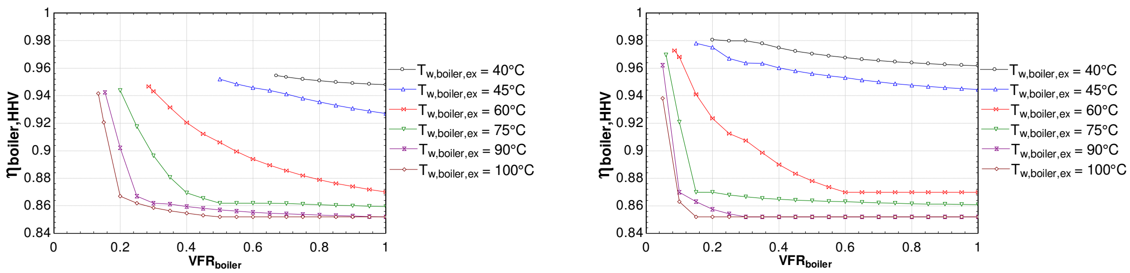

Fig. 4. Sensitivity of the gas condensing boiler efficiency to water flow rate ratio (with respect to nominal flow rate) for different exhaust water temperature setpoint: (a) at PLR = 1, (b) at PLR = 0.3

The influence of the water flow rate on the condensing boiler efficiency is clear. When controlling properly the water flow rate in the boiler, high efficiency can be achieve regardless of the boiler exhaust water temperature. Anticipating a bit the rest of the papers, these observations paves the way for the optimization of the systems with a trade-off between reducing the flow rates (and thus the consumption of the auxiliaries), and reducing the water temperature decreasing the heat losses in the distribution system and slightly increasing the boiler efficiency.

3. Whole system simulation and optimization

This section presents a first approach to analyze the performance of the whole system when integrated into a building. It aims to give an overview of the difficulties but also the possibilities to further optimize a system design and operation. To do so, a reference building, where the cooling and heating loads are known, is considered. This building is coupled to the primary system investigated in the previous section using a simplified distribution model.

3.1. Reference building

The reference building loads are evaluated based on a reference office building model developed in the frame of IEA EBC Annex 59 project[1]. Only a reference floor of this building is actually modeled with 5 occupied zones (4 peripheral zone and one core zone) and according to the commonly used RC-equivalent network technique [4]. In this model, the total building loads are obtained by duplicating 5 times the reference floor to obtain a building with 5 floor.

3.2. Model

In the first approach, the model is simplified to demonstrate the methodology for system analysis. The schematic given in Fig. 5 shows the model components. The chilled water and hot water distribution system are considered as a two circuit (one for the chilled water and one for hot water) with a pressure drop and a pump associated. The circuits are connected to the building which is just considered as a cooling load and a heating load. The boiler and the chiller are supposed to produce the required heating/cooling energy.

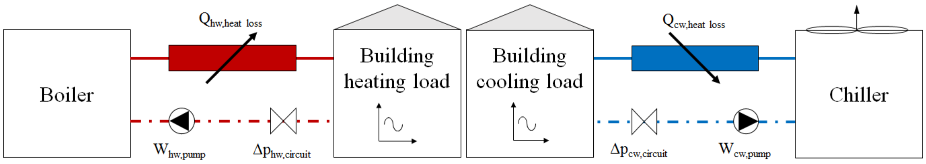

Fig. 5. Schematic diagram of the production and distribution system integrated in the building as modeled in the first approach

The pressure drop in the circuits is evaluated in nominal conditions based on a reference building HVAC system also developed in the frame of IEA EBC Annex 59 project[1]. It considers the nominal pressure drop of the primary system given in the manufacturer datasheet, the linear pressure drop (considering 200 Pa/m_{pipe}) and the pressure drop in the terminal unit. It gives respectively for the cooling and heating system 97.1 kPa (for 19.44kg/s) and 93.8kPa (for 9.89kg/s).As first assumption, the actual pressure drop in the circuit is evaluated as:

$$\Delta p_w = \Delta p_{w,n} \cdot \left(\frac{\dot{M}_w}{\dot{M}_{w,n}} \right)^2 \tag{1}$$

The pump consumption is then evaluated based on:

$$\dot{W}_{pump} = \dot{M}_w \cdot v_f \cdot \frac{\Delta p_w}{\eta_{pump}} \tag{2}$$

with v_f the specific volume of the fluid and η_{pump} the pump efficiency.
The heat losses between the pipe and its environment can be written as:

$$\dot{Q}_{loss} = \dot{M}_w \cdot c_w \cdot (T_{w,su} - T_{amb}) \cdot (1 - \exp(-NTU)) \tag{3}$$

$$NTU = UA \div (\dot{M}_w \cdot c_w) \tag{4}$$

with T_{amb}, the ambient temperature (considered constant and equal to 20°C) and NTU, the Number of Transfer Units. The overall heat transfer coefficient UA is calculated given as input the pipe dimensions and insulation materials. In this case the value considered are UA_{cw} = 101.87W/K and UA_{hw} = 97.9W/K.

3.3. Results

Based on the observation made in the first section of the paper, different scenarii were tested for the operation of the systems. Results are presented for the cooling system in Fig. 6 and for the heating system in Fig. 7. For both simulations, hourly weather data of a typical Frankfurt year are used. For the heating system, the influence of the boiler exhaust water temperature and the selected water flow rate are evaluated considering a minimum boiler supply water temperature of 25°C while for the cooling system the chiller operating conditions presented in Table 1 are still considered. For the cooling system, the influence of the exhaust water temperature is significant. However the impact of the water flow rate is quiet obvious and is consistent with the line of work presented in this study. There is a clear trade-off between chiller performance and auxiliary’s consumption. For the heating system, the observation made in the first section for the boiler alone are quite similar with water flow rate having an important impact on the boiler efficiency and then on the whole system consumption. The integration of the heat emitters should also impact the system performance with additional auxiliary consumption and with different average emission temperature benefiting to the highest boiler exhaust water temperature.

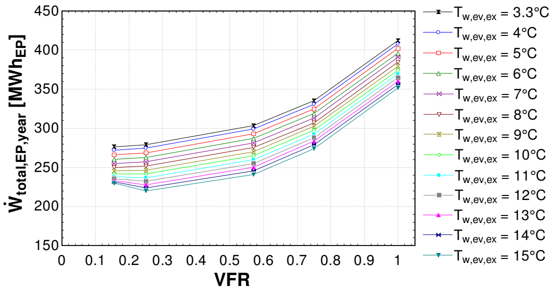

Fig. 6. Influence of the evaporator exhaust water temperature and the VFR on the annual primary energy consumption of the cooling system.

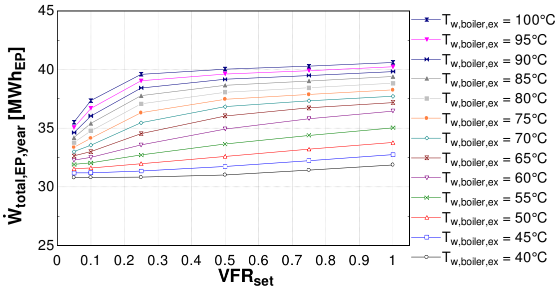

Fig. 7. Influence of the boiler exhaust water temperature and the VFR on the primary energy consumption of the whole heating system.

4. Conclusion

From these results, it can be said that for a required cooling or heating load, it exists a combination of water flow rate and supply temperature that results in a minimum primary energy consumption. As observed, for an air-cooled chiller, it is beneficial to supply the required cooling load with the highest water temperature possible. In the gas-condensing boiler, its supply water temperature is clearly the most influent parameter. The influence of its exhaust water temperature is not as important. The use of low temperature heating supplied by a gas condensing boiler is than questionable if an optimal water flow rate control is available. From the system integration point of view, it is then clear that the optimal operating conditions of the whole system can be different from the optimal primary system operating conditions. Both design and operation of the system should consider those influences and take into consideration the trade-off between primary system performance, auxiliaries' consumption and secondary system efficiency. However, to practically achieve an optimal design and operation of a system, it is essential to develop a methodology based on clear models for each component of the system and capable of representing their performance sensitivity to fluid temperature, flow rate and part load.

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