Optimising Hydronic Distributions for Energy Efficiency

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Abstract

Optimising the hydronic network in a HVAC system reduces energy consumption and improves the control and delivery of comfort.

Condensing boiler and chiller efficiencies are directly influenced by the return water temperature of the system with potential loss of efficiency of up to 10-15%. Understanding the respective impact of proportional versus on-off control and of variable versus constant flow circuits on return water temperature is therefore essential and is reviewed.

The importance of a good pressurisation system is often neglected when talking about energy efficiency. However, avoiding water make-ups due to incorrect pressurisation allows to limit scaling and the ingress of oxygen leading to corrosion. Both of these effects are briefly examined in terms of their impact on energy consumption.

In cooling systems, electrical pumping costs represent up to 7% to 17% of the total cooling energy consumption. A methodology combining the use of differential pressure controllers and remote Dp sensor for the variable speed pump will also be discussed, which allows reducing the pumping costs by up to 30-40% compared to a non-optimized situation.

In heating systems, the trend to lower temperature regimes requires higher precision in radiator flow adjustment and control. This emphasizes the importance of delivering the required temperature with precision by working with modern components with low hysteresis, low influence of water temperature and differential pressure.

Keywords – hydronics; pressurisation; control; balancing; energy efficiency

1. Introduction

Environmental concerns, legislation and rising energy prices are dramatically increasing the need for energy efficiency in buildings. There are various ways to improve this efficiency, and as HVAC systems account for up to 50% of a building's energy usage, they are under particularly intense scrutiny.

The energy consumption of a building can be reduced by improving its infrastructure with new insulation, windows etc. This has a major effect but involves usually heavy investments with long pay-back times. In addition, after performing such a work, the entire HVAC system needs to be readjusted.

Optimising hydronic distribution in HVAC systems is the most cost-effective solution to reduce energy consumption; the effects are immediate and substantial. In fact, optimising the hydronic distribution of an existing system can reduce its energy consumption by up to 30% (depending on the initial status of the plant) while delivering a high comfort level. This overall reduction can however be achieved only through a series of measures bringing one-by-one small improvements. We will examine a few in this article.

2. The issue of return water temperature for condensing boilers

To achieve higher efficiency, a condensing boiler is designed with an exchanger-condenser that reduces the temperature of flue gases down to 5-15°C above the return water temperature. This allows condensing the water vapour produced by the combustion, delivering thereby an efficiency increase by latent heat recuperation that can theoretically reach 11%.

Clearly, the latent heat gain is achieved by a condensing boiler only if the return water temperature is kept below a limit that brings the exhaust gases below the vapour dew point. This limit is typically of 54-55°C for condensing boilers burning natural gas.

In order to maximize the fraction of the heating season during which condensation occurs, it is fundamental to control supply water temperature in function of the outdoor conditions according to a heating curve, as displayed in figure 1 for a chosen design temperature regime of 80-60°C. It can be observed on this graph that condensation will be obtained (i.e. return water temperature below 55°C) only when the outdoor temperature is above 0°C. Considering for instance the temperatures registered hourly in Greenwich during winter 2010-2011, this tells us that a boiler operating there with 80-60°C design temperature regime will be condensing during approximately 6192 hours.

The above numbers apply provided that the system works perfectly as intended by design. When flows are not properly distributed in a system, some parts of the plant are in overflow while others will suffer from chronic underflows. Tenants in the unfavoured parts of the building will raise complaints. In reaction, maintenance people will increase the speed of the pump leading to global overflow compared to the real needs and/or lift the heating curve. Both measures will reduce the condensing opportunity. Indeed, a global overflow in the system leads to lower temperature difference and therefore a higher return water temperature. The dashed line in figure 1 illustrates the effect of a 50% overflow on the return water temperature curve resulting in a reduction of the condensing time to 5424 hours (-12.4%) for the considered case.

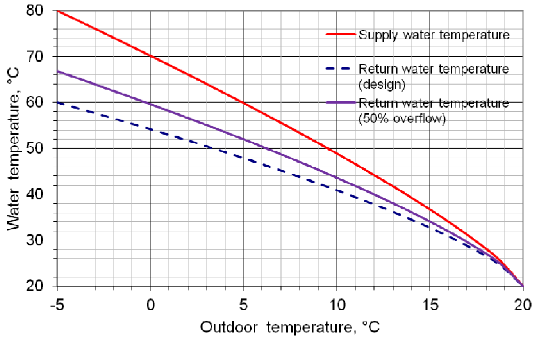

Fig. 1 Heating curve and resulting return water temperature curves for a 80-60°C temperature regime and a design outdoor temperature of -5°C

It is thus clear that a careful adjustment of flows in the hydronic system is an essential step to obtain in practice the energy savings promised by the condensing boiler technology.

This is clearly exemplified by the two-step renovation of a complex of 12 residential buildings in Toulouse, France [1]. After replacement of the existing conventional boiler in summer 2007, an energy saving of 9.6% was obtained during winter 2007-2008, see figure 2. The second step of the renovation performed in summer 2008 consisted in an audit of the hydronic system and a readjustment of design flows according to a systematic balancing methodology. It delivered an additional 12.3% energy saving the next winter.

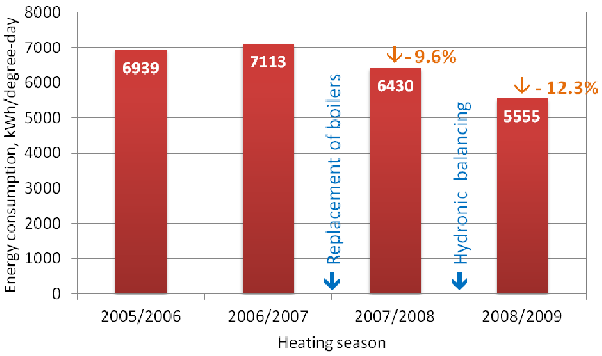

Fig. 2 Evolution of energy consumption of the Empalot (France) residential complex [1]

3. Impact of control mode and circuit type on return water temperature in cooling

Chiller efficiency is usually indicated by the Energy Efficiency Ratio (EER). In order to keep the EER of a chiller as high as possible at partial load, a key element is to avoid a degradation of the log mean temperature difference between the chilled water and the refrigerant. With a constant chilled water supply temperature as generally considered in cooling, this means that one should avoid all causes of decrease of the chilled water return temperature at partial load.

As an indication of the importance of this point, the results of a simulation performed on a chiller manufacturer simulator for a chiller of 703 kiloWatts with water condenser temperatures of 29.5-35°C and chilled supply water temperature of 7°C indicates a 15% drop of the EER when the chilled return water temperature drops from 12.5°C to 10.5°C.

In order to determine the evolution of the return water temperature at partial load, one must look at what happens on the terminal unit side.

Let us first consider the case of proportional control on a variable flow circuit with fan-coil unit equipped with a two-way control valve and assumed to be properly balanced (figure 3a). Since the flow is progressively decreased at reduced load, the temperature difference through the unit (and thus through the circuit) regularly increases as displayed by the red curve in figure 4 for a 7-12°C temperature regime. Hence, a stable and accurate proportional control of the cooling output of a terminal unit with a variable flow circuit benefits to the chiller EER.

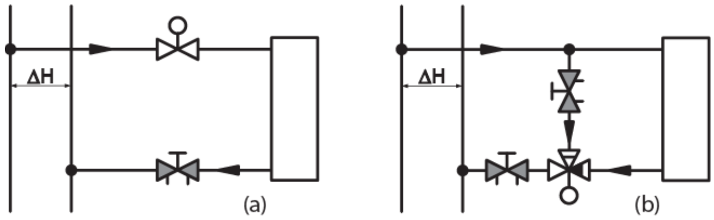

Fig. 3 (a) Two-way variable flow circuit; (b) Three-way diverting circuit

Let us now turn our attention to 3-way diverting circuit also with proportional control (figure 3b). Such a circuit is often used in variable flow systems at the end of branches to maintain a minimum flow for the pump but also to avoid warming up of the supply water due to heat gains in the piping. With such a circuit, the evolution of the temperature difference through the unit at partial load is the same as for the 2-way circuit. However, when the 3-way control valve progressively closes, there is an increasing amount of flow that is bypassed and that cools down the global return of the circuit as illustrated by the blue curve in figure 4. It is therefore clear that the use of this circuit should be kept to the strict minimum to ensure required minimum flow since it systematically deteriorates the return water temperature.

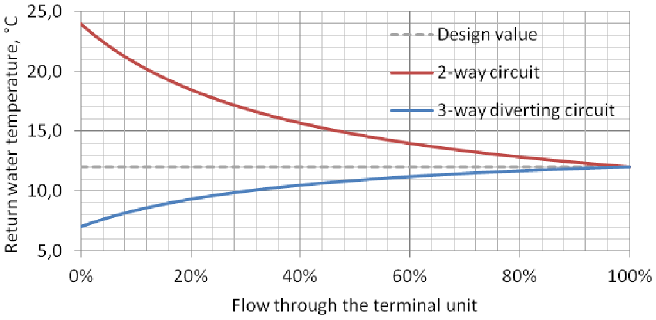

Fig. 4 Return water temperature evolution at reduced load with proportional control
for a 7-12°C design temperature regime and a room temperature set-point of 24°C

In the above cases, stable and accurate proportional control has been assumed. For cost saving reasons, it happens regularly that on-off control is preferred. It also happens regularly that proportional control deteriorates due to incorrect valve sizing leading to an uncontrollable on-off type of behaviour. Let us consider thus the two circuits of figure 3 with on-off control.

Part load conditions in a plant uniformly equipped with on-off control circuits can be monitored by counting the number of units that are 'on' at one moment in time. At 50% load, we should have in average 50% of the units 'on' and 50% of the units 'off'.

If all circuits are 2-way on-off circuits, when some circuits are 'off', there is less total flow and the pressure drops in the piping decrease with the square of the flow decrease. There is therefore higher available differential pressure at all points in the system, resulting in higher flow than per design in the circuits that are 'on'. Due to the nonlinear heat output characteristic of terminal units, the heat output of the units only increases moderately with the flow above design flow [2]. Thus, with a higher flow than per design and a heat output that does not increase much, the temperature difference through units decreases at partial load with an on-off control system applied to 2-way circuits. Figure 5 depicts this effect for a model case. It can be observed for this model case approximately a 2°C drop of return water temperature which will affect the chiller EER as discussed above.

If all circuits are 3-way on-off circuits, when some circuits are 'off', the flow is bypassed in these circuits so that the total flow in the plant does not change. However, as flows are bypassed in the proportion of the number of units that are 'off', the return water temperature decreases linearly with the load in the system (see blue curve in figure 5).

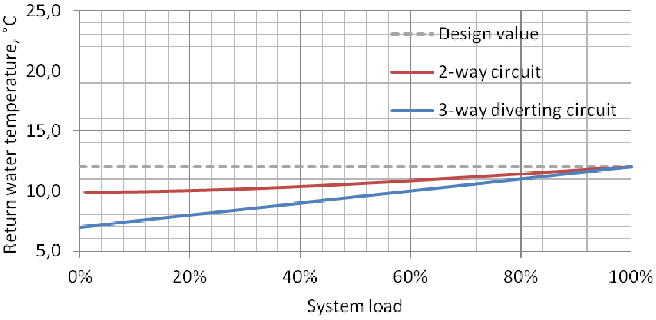

Fig. 5 Return water temperature evolution at reduced load with on-off control
for a 7-12°C design temperature regime and a room temperature set-point of 24°C.
(Model case with 100 identical units, pump head of 150 kPa and 20 kPa in terminal units)

It is thus clear that amongst the different considered circuits, the 2-way variable flow circuit with proportional control should be the preferred circuit provided that stable and accurate control is ensured by proper selection and sizing of the control valves.

Interestingly, this issue has been addressed in the renovation of the cooling system of two buildings of Hong-Kong Polytechnic University [3]. Specifically, differential pressure controllers have been added at the inlet of branches of on-off controlled fan-coil units and across control valves of air handling units to prevent flow increase at partial load in fan-coil units and guarantee stable control of air handling units. The graph presented in figure 6 displays the measurements performed before and after the renovation work delivering a 16.5% reduction of chiller annual energy consumption.

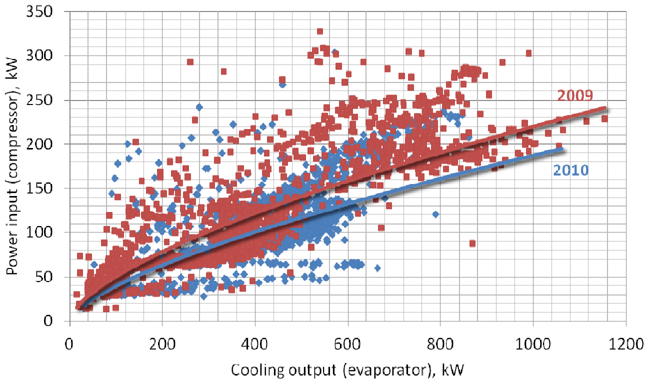

Fig. 6 Measurements before and after application of differential pressure controllers on branches of on-off controlled fan-coil units and across control valves of air-handling units [3]

4. Importance of a correct pressurisation

When addressing energy efficiency, pressurisation rarely comes up as a point of attention. This is forgetting that an improper pressurisation due to incorrect sizing or poor quality of the expansion system leads to frequent water make-ups to compensate static pressure loss.

Fresh water contains calcium bicarbonates that precipitate into limescale at the hotter points of boilers leading to extra energy consumption as limescale acts as an insulation to the heat transfer. The extent of the effect does not seem to be the object of proper analysis in the literature although often cited test results from the University of Illinois and the US Bureau of Standards would indicate an efficiency loss of 9% for 1 millimetre of scale deposit.

Fresh water also contains gases (essentially nitrogen and oxygen) in the form of micro-bubbles as well as in dissolved form in the water. Regular water make-up is thus a channel for the ingress of oxygen in the system leading potentially to substantial corrosion. The corrosion of internal surface of pipes affects the linear pressure drops in a double way. First, rust is thick and decreases the effective internal diameter of corroded pipes, resulting in higher velocity for the same flow. Second, rust is rough which has an obvious impact on pressure drops. Increase between 15 and 70% of linear pressure drops of aged pipes have been reported in [4]. Although this seems high a simple calculation performed for a DN 25 pipe from Steel DIN 2440, ISO 65 series indicates indeed increase of linear pressure drops between 15 and 80% for light and medium corrosion.

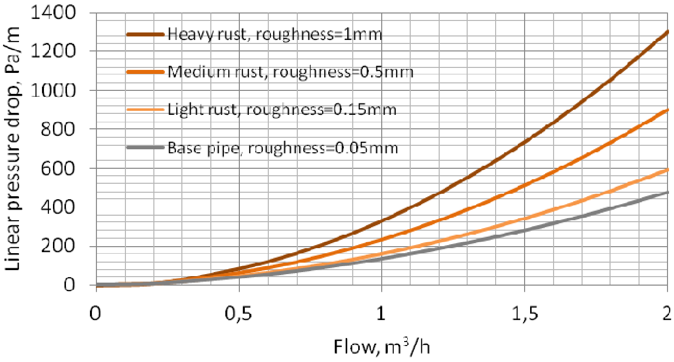

Fig. 7 Linear pressure drops in DN 25 pipe from Steel DIN 2440, ISO 65 series

This emphasizes the importance of an efficient, correctly sized and commissioned pressure maintenance system that avoids the ingress of oxygen in the hydronic network.

5. Enhanced pumping energy savings through differential pressure control

Pumps are the main energy consuming devices in water distribution. Using the estimation formula published in [2] with recent values of efficiencies and energy costs, one finds that pumping energy accounts for 7 to 17% of the total energy costs of a water-borne cooling system while it only represents 0.5 to 1.5% in a heating system. This is confirmed by [5] for heating systems in commercial buildings.

When a system is equipped with a variable speed pump (VSP), one could wonder if the use of differential pressure controllers is really needed as both devices seem to work according to the same basic principle: controlling the differential pressure at one point in the system. Variable speed pumps are meant to maximize pumping energy savings at varying load in a variable flow system. They do act where they are installed, on the total flow going through them, based on the differential pressure sensed at one location by their Dp sensor. Even if multiple sensors are used, at one moment in time, a VSP can only adapt its speed according to the signal of one of the sensors.

Thus VSP cannot guarantee by themselves a stable and accurate control to all circuits distributed all over the system. This is true whatever the control mode and Dp sensor location that is selected. Differential pressure controllers are required to protect local control valves from large differential pressure variations experienced at varying load in variable flow systems.

When differential pressure controllers are used consistently over a variable flow system, enhanced pumping energy savings can be obtained by using a remote Dp sensor for the VSP. This is made possible because differential pressure controllers are self-acting balancing devices adapting their opening according to the variations in the system. Without differential pressure control, the use of a remote Dp sensor in the middle or the end of the system always lead to having some circuits unable to deliver their design heating/cooling output under part load conditions.

The process to obtain optimum pumping energy savings together with good controllability of all circuits works in three steps:

1. Perform dynamic balancing with stand-alone Dp controllers on each branch/zone or on each unit by using pressure-independent control valves.
2. Install the VSP Dp sensor on the index, Dp controlled, branch or circuit.
3. Adjust the set-point of the VSP to the largest required differential pressure amongst all Dp controlled branches/circuits.

This last step ensures that all stabilized areas will receive enough primary differential pressure at low load. In order to implement this process, it is warmly recommended to perform a complete differential pressure calculation of the system.

Results obtained after renovation with Dp controllers for Hong-Kong Polytechnic University [3] have demonstrated a 32% year-on-year reduction of pumping energy.

6. Accuracy requirements for thermostatic radiator valves

Over the last few years, design temperatures for heating systems have been gradually decreased. While the 90-70°C temperature regime was prevailing in Europe until the middle of the nineties, the 80-60°C regime has been adopted in the years 2000 to see appearing nowadays temperature regimes as 70-50°C and lower.

Although this is beneficial to the return water temperature and thus for preserving the high efficiency of condensing boilers, this induces a higher sensitivity of the room temperature to the controlled flows in radiators. Table 1 provides the admitted flow deviations for different temperature regimes in order to keep the room temperature ±0.5°C around its set-point. A growing need in accuracy can be observed for modern temperature regimes.

Table 1. Admitted flow deviations for keeping room temperature ±0.5°C around its set-point

T_{ext}, °C	T_{supply}, °C	T_{return}, °C	T_{room}, °C	Admitted flow deviation
-10	90	70	20	±13%
-10	80	60	20	±11%
-10	70	50	20	±9%
-10	60	40	20	±7%

Room temperature control performed with thermostatic radiator valves depends mainly on the following characteristics of the thermostatic head and valve that should have a low hysteresis (around 0.3-0.4K), a low influence of the water temperature (from 0.3 to 0.7K), a low influence of differential pressure (around 0.3K) and correct response time (≤ 25 minutes) according to test specifications provided in EN 215.

A recent study performed in Technische Universität Dresden [6] demonstrates the benefit of working with higher quality thermostatic heads. The study shows that replacing thermostatic heads older than 1988 (pre-CEN marking) by new ones results in no target room temperatures undershot, less overheating and greater adherence to target values. This improvement in room temperature control provides energy savings of 7% saving in existing 90-70°C plants and 5% saving in 70-55°C plants.

7. Conclusion

In order to maintain the operational efficiency of condensing boilers and chillers at the highest possible level, care must be taken to avoid degradation of return water temperature. In general, flows must be correctly adjusted to avoid global overflows leading to low temperature differences and two-way variable flow circuits with proportional control should be preferred. For heating in particular, supply water temperature control is must to lower the return temperature on the largest possible part of the heating season.

The quality, sizing and commissioning of pressure maintenance systems is also an important element. Scale deposit can impact boiler efficiency by about 10% while undesirable pipe ageing may lead to 15 to 80% increase of linear pressure drops.

Pumping cost optimisation is a process that may easily lead to operational difficulties. The key element is to reduce pumping costs up to the very point at which full design flow can be delivered at any time to any place with stable differential pressure at all locations for performing quality proportional control. This can be achieved by combining the use of self-acting differential pressure controllers with remote Dp sensor for the variable speed pump through a three step methodology.

With the evolution of design temperature regimes, there is a increased demand in control accuracy on thermostatic heads and valves. The easy replacement of older equipment by newer generation thermostatic heads has demonstrated interesting energy saving results.

In fact, optimising the hydronic distribution of an existing system by combining some of the above discussed techniques can in average reduce its energy consumption by up to 30% while delivering a high level of comfort.

Acknowledgment

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