Chapter 7

Energy Efficiency of Hydronic Heating System in Retrofitted Buildings

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Additional information is available at the end of the chapter

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Abstract

Since central-based heating systems with radiators are among the most widely used heating systems in Europe, retrofit measures should include heat distribution and heat emission elements. One of the most cost-effective measures for heating systems is the replacement of the heat generator and circulating pump while preserving the distribution system and heat emitters. Reducing the heating demand results in an oversized existing heating system and thus enables a reduction in flow rates and supply temperatures. These steps should be taken to enhance the efficiency of the heating system without affecting the level of thermal comfort. This chapter focuses on the issue of energy efficiency in retrofitted buildings by optimizing the existing heating systems. The heating equipment is considered as one system, and it is not intended to improve only individual component efficiency. The optimization goal is to achieve a recommended or prescribed thermal comfort level with minimal energy use.

Keywords: energy performance, energy efficiency, hydronic heating, heat emission, thermal comfort, retrofit analysis

1. Introduction

In Europe, the building sector is responsible for 40% of the region's energy consumption and 36% of its CO_2 emissions. Because of high-energy saving potentials, the building sector has become one of the priority areas to meet the EU's targets for 2020 and 2050 [1]. The Energy Performance of Buildings Directive [2] promotes nearly net-zero energy buildings as a mandatory regulation within 2020. This means that new buildings need less than 30–50 kWh/m^2 per year, while existing buildings consume approximately 250 kWh/m^2 per year. Therefore, most of the energy consumption is attributable to the existing building stock. Energy savings obtained from retrofitting existing buildings are more significant than the ones that can be obtained with new buildings.

This fact is reflected in the Energy Efficiency Directive [3] through the requirements for:

1. Public sector to renovate 3% of the central government building stock annually to high-energy performance level (nearly net-zero energy buildings).

2. Energy companies to reduce energy sales by 1.5% every year among their consumers.

Most of the energy savings of the retrofit can be contributed by two key targets: reducing heating demand and increasing the efficiency of HVAC systems. An important factor in achieving the expected reduction target is improving the efficiency of systems without affecting thermal comfort. Typical retrofit measures to reduce the heating demand include applying insulation layers on walls and/or replacing windows. Little attention is given to how the improvements on the building's envelope affect the settings and efficiency of the heating system. Basically the increase of insulation reduces the heating demand which in turn can reduce flow rates and/or supply temperatures. Reducing the supply temperature makes low-temperature heating system interesting and economically viable [4, 5].

Since central-based heating systems with radiators are among the most widely used heating systems in Europe [6], retrofit measures should include heat distribution and heat emission elements. One of the most cost-effective measures on heating systems is the replacement of the heat generator and circulating pump while preserving the distribution system and heat emitters [7]. Reducing the heating demand results in an oversized existing heating system and thus enables a reduction in flow rates and supply temperatures. These steps should be taken to enhance the efficiency of heating system without affecting the level of thermal comfort.

This chapter focuses on the issue of energy efficiency in retrofitted buildings by optimizing the existing heating systems. The heating equipment is considered holistically and it is not intended to improve only individual component efficiency. The following steps are presented:

- The need for optimization
- Impact of heating technology on the optimization process
- Optimization of the hydraulic network

An integrated methodology for energy efficiency in retrofitted buildings is proposed through coupling active and passive strategies specifically tailored for application in traditional heating systems. The main results show how the applications of specific building energy retrofit actions could increase the energy efficiency of the heating system without compromising thermal comfort. Finally, a system optimization is also determined by different constraints, i.e., the use, economy rules, and technical regulations. Nevertheless, the optimization and improvement of the heating system efficiency in retrofitted buildings give a unique opportunity that new buildings are not given, namely, the possibility of energy saving [8].

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2. Building envelope refurbishment

Contemporary type of building construction with smaller heat losses and demands for increased comfort requires new concept of radiator construction and regulation of heat output. The heat emission of a radiator depends on size, design, and mean temperature difference between the radiator surface and the indoor temperature—excess temperature. At given thermal constraints, the effect of geometrical and thermal parameters of a radiator could be optimized [9]. On the other side, to maintain the desired heat output, it must be regulated according to the condition of thermal comfort and outdoor conditions.

Control of the heat output can be realized by changing the radiator surface, by changing the heating water inlet temperature (temperature control), or by changing the mass flow through the radiator (mass control) [10]. The first option is not physically feasible; another option is feasible using relatively complex control system with three-way mixing valve. This control method is used primarily in the central control unit, which regulates the temperature of heating water to a large number of radiators. For local regulation of the heat output, the most commonly used principle is by varying the mass flow of water through the heater, where the flow change is controlled by a throttle valve. This system is easy and most affordable, so almost all systems of local regulation of radiators are based on "throttling." From the standpoint of regulation, this system has several shortcomings. Since the radiator heat output varies exponentially according to the mass flow rate, in the case of large throttling, a small change in valve position (small change in flow rate) causes a disproportionately big change in heat output. This situation occurs at reduced heat output, oversized radiator (also as a result of proper dimensioning taking into account the heating-up reserve for intermittent/reduced mode of operation of heating system), inappropriate (too high) water inlet temperature, or because of internal and external heat sources.

Another problem is the heat output at reduced water flow rate [11]. Due to the smaller water speed in the radiator, the retention time is longer, resulting in a lower water temperature at the exit of the radiator and a lower average temperature of the radiator. Low water flow rate also causes mixing of inlet water with colder water in the radiator. These result in a less effective inlet water temperature, so the heat emitted is significantly different—lower—than expected, according to standard calculation methods with respect to excess temperature. Heating systems mostly operate at variable loads, which depend on the regulation. One of the tasks of heating systems is not only to provide the necessary heat but also to adapt the heat output as quickly as possible to the change of heat load. From this viewpoint, it is recommended to have heating systems (including radiators) with low thermal inertia.

The refurbishment of the building envelope affects the thermal characteristics, which have a significant effect on the heating system operating conditions and consequently on its energy efficiency. To ensure the latter, we must consider the following aspects: the efficiency of each component and the efficiency of the system, which is determined with the interactions of individual components. For the whole system efficiency, the following conditions must be met:

- properly sized and set system elements (radiators, valves, piping system, pumps, heat generators)
- setting of local and central regulation
- optimal hydraulics

These conditions apply both to new and existing buildings. Most of the heating system components are already determined in existing buildings. The refurbishment of the building envelope therefore requires an adjustment of existing system components to achieve optimal operation and consequently proper energy efficiency. The fundamental difference between the optimization of an existing and new system is that optimal operation of existing systems is achieved with adjusting their settings, whereas the optimization of new systems is based on selecting components of proper quality and characteristics.

Optimization and efficiency are closely connected with internal environment quality and operating conditions. Internal environment conditions that enable a proper quality of living or a proper thermal comfort level must be considered [12]. Thermal comfort level of a certain thermal environment directly determines energy use. Therefore, we cannot discuss the heating system efficiency without the achieved thermal environment. The optimization goal is to achieve a proper thermal comfort level with minimal energy use.

The refurbishment of the building envelope results in a decrease of the required heat for heating and the power of radiators. Therefore, operation of the heating system has to be adjusted to the new operating conditions. After the building envelope refurbishment, the heating load of the outer rooms generally decreases more significantly than at the inner rooms. The heating load decrease depends on the improvement of the building envelope thermal transmittance and the fraction of outer wall area. A larger fraction of outer wall area results in a more significant decrease in the required radiator power. However, thermal insulation does not cause a significant decrease in the required radiator power for inner rooms. Consequently, it is important that we after the building envelope refurbishment properly adjust the thermal power of radiators according to the heating load decrease in the room in which they are installed.

3. Radiator heat output

The radiator thermal power is defined by the supply temperature and the mass flow. For the determination of the required thermal power of the radiator heat, losses due to transmission (Eq. (1)) must be considered:

$$\dot{Q}_T = U_e \cdot A_e \cdot (t_i - t_e) \tag{1}$$

where $\dot{Q}_T$ is the heat losses due to transmission; U_e is the thermal transmittance; A_e is the area of external wall; t_i is the internal temperature; t_e is the external design temperature.

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The change of the heat load before and after the envelope refurbishment is therefore:

$$\frac{\dot{Q}_{T1}}{\dot{Q}_{T2}} = \frac{U_{e1} \cdot A_e \cdot (t_i - t_e)}{U_{e2} \cdot A_e \cdot (t_i - t_e)} \quad (2)$$

where index 1 designates the properties before the refurbishment and index 2 the properties after the latter. It is assumed that the areas of external walls as well as internal and external temperature do not change.

The required heat is provided by the radiator, whereby its thermal power is defined according to Ref. [13]:

$$\dot{Q} = A \cdot \Delta t_{ex}^{n} \quad (3)$$

where $\dot{Q}$ is the thermal power of radiator; A is the radiator area; Δt_{ex}^{n} is the excess temperature; N is the radiator exponent.

The radiator excess temperature is defined as a logarithmic temperature difference between the average radiator surface temperature and the room temperature:

$$\Delta t_{ex} = \frac{t_S - t_R}{ln\frac{t_S - t_i}{t_R - t_i}} \quad (4)$$

where t_S is the supply temperature; t_R is the return temperature; t_i is the room temperature.

The change of the emitted heat by the radiator is defined with the following relation:

$$\frac{\dot{Q}_1}{\dot{Q}_2} = \frac{A_1 \cdot \Delta t_{ex1}^{n}}{A_2 \cdot \Delta t_{ex2}^{n}} \quad (5)$$

where A_1 is the radiator area before the refurbishment; A_2 is the radiator area after the refurbishment; Δt_{ex1}^{n} – is the excess temperature before the refurbishment; Δt_{ex2}^{n} – is the excess temperature after the refurbishment.

If we assume that the radiator area does not change and that the radiator exponent is constant, the change of the emitted heat depends only on the excess temperature change:

$$\frac{\dot{Q}_1}{\dot{Q}_2} = \left(\frac{\Delta t_{ex1}}{\Delta t_{ex2}}\right)^{n} \quad (6)$$

The heat required for heating is provided with the flow of heated water through the radiator. The heat emitted from water depends on the mass flow and cooling down of the water:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \left(t_S - t_R\right) \tag{7}$$

where $\dot{Q}$ is the radiator thermal power; $\dot{m}$ is the water mass flow through the radiator; c_p is the water specific heat; t_S is the supply temperature; t_R is the return temperature.

The change of the emitted heat is so defined with the following relation:

$$\frac{\dot{Q}_1}{\dot{Q}_2} = \frac{\dot{m}_1}{\dot{m}_2} \cdot \frac{\left(t_{S1} - t_{R1}\right)}{\left(t_{S2} - t_{R2}\right)} \tag{8}$$

where index 1 designates the state before while index 2 designates the state after the refurbishment.

3.1. Radiator heat output at various conditions

From Eqs. (2), (6), and (8), the influence of building thermal envelope change on the change of radiator heat output can be seen. It can also be seen that this change can be compensated with:

- Changing the water supply temperature (Eq. (6))
- Changing the water mass flow (Eq. (8))

Hereby, we considered the interdependence between Eqs. (6) and (8). At constant water temperature, the return and excess temperatures change because of the water mass flow change. The interdependence between water mass flow and the radiator excess temperature can be depicted graphically [14, 15]. **Figure 1** shows the emitted heat of a radiator with radiator exponent n = 1.3 at standard temperature conditions: supply temperature t_S = 75°C, return temperature t_R = 65°C, and room temperature t_i = 20°C.

The emitted heat is shown as a relation between the heat output at standard conditions $\dot{Q}_0$ and at other conditions $\dot{Q}$. The supply and return temperatures are included with the supply and return excess temperature and the dependence between heat output and mass flow is expressed as a ratio between the actual and standard mass flow. Thereby, all the influences of the heating system on the heat output are considered. With such a diagram (or numerically with an iterative procedure), one can determine the new operating conditions for an existing radiator.

Figure 2 shows an example of the effect of heat loss reduction on the change of radiator operating conditions.

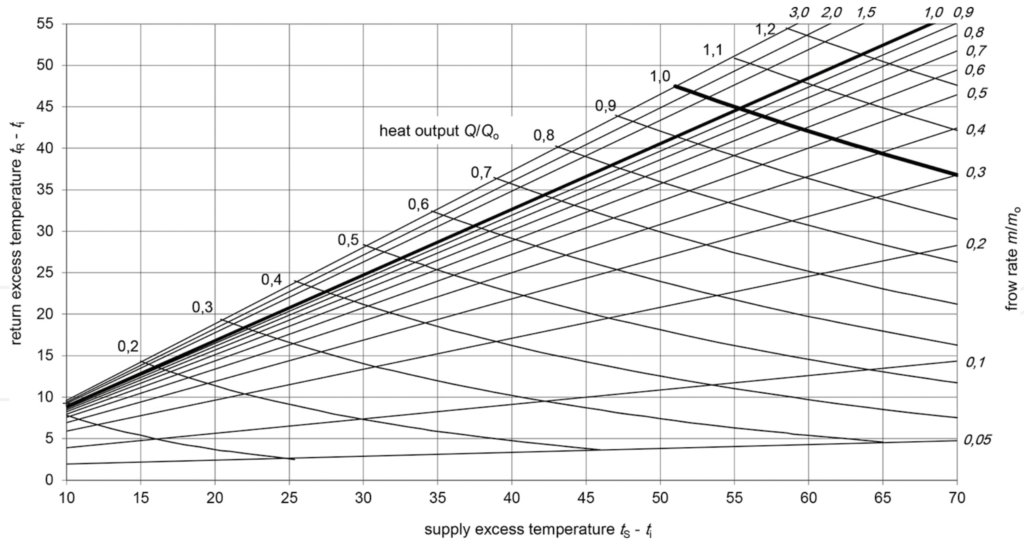

Figure 1. Heat output of the radiator at operating conditions 75/65/20 [13, 15].

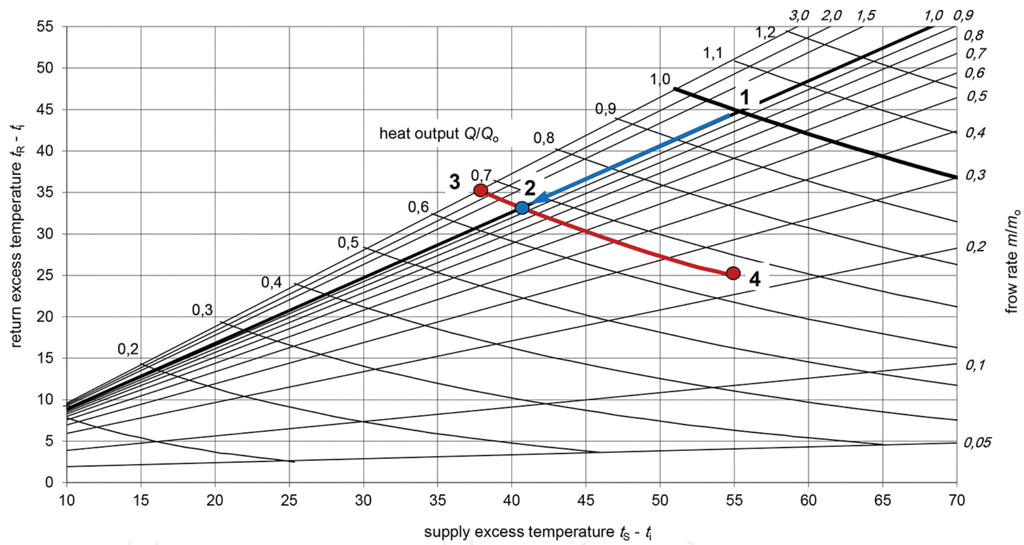

Figure 2. Heat output at the reduced heat demand for 33%.

Point 1 represents the radiator thermal power before the refurbishment, whereby the temperature regime 75/65/20 [13] was assumed. If the radiator is properly sized and selected, the thermal power is $\dot{Q}/\dot{Q}_0 = 1.0$, the mass flow is $\dot{m}/\dot{m}_0 = 1.0$, and the logarithmic excess temperature is 49.83 K. The refurbishment of the building envelope results in a decrease in the required radiator thermal power, e.g., 33%. Therefore, the reduced heat output of the radiator is $\dot{Q}/\dot{Q}_0 = 0.67$. Maintaining the (unchanged) mass flow $\dot{m}/\dot{m}_0 = 1.0$ (blue line), we reach the required heat output at the mean logarithmic excess temperature of the radiator 37 K—point 2. However, the radiator reaches the same heat output at different supply and return water temperature combinations. Possible combinations are shown as a red line in **Figure 2**; characteristic points on this line represent the following operating conditions:

—Point 2: mass flow $\dot{m}/\dot{m}_0$ = 1.0, supply temperature t_S = 62°C, return temperature t_R = 53°C.

—Point 3: mass flow $\dot{m}/\dot{m}_0$ = 3.0, supply temperature t_S = 57°C, return temperature t_R = yy°C.

—Point 4: mass flow $\dot{m}/\dot{m}_0$ = 0.24, supply temperature t_S = 75°C, return temperature t_R = 45°C.

The difficulty in determining the heating system operating parameters is that the reduction in the required thermal power is generally not the same for the other rooms (other radiators). For a room with a higher fraction of external surfaces, the reduction in the required thermal power is more significant, e.g., 40%. This case is depicted in **Figure 3**.

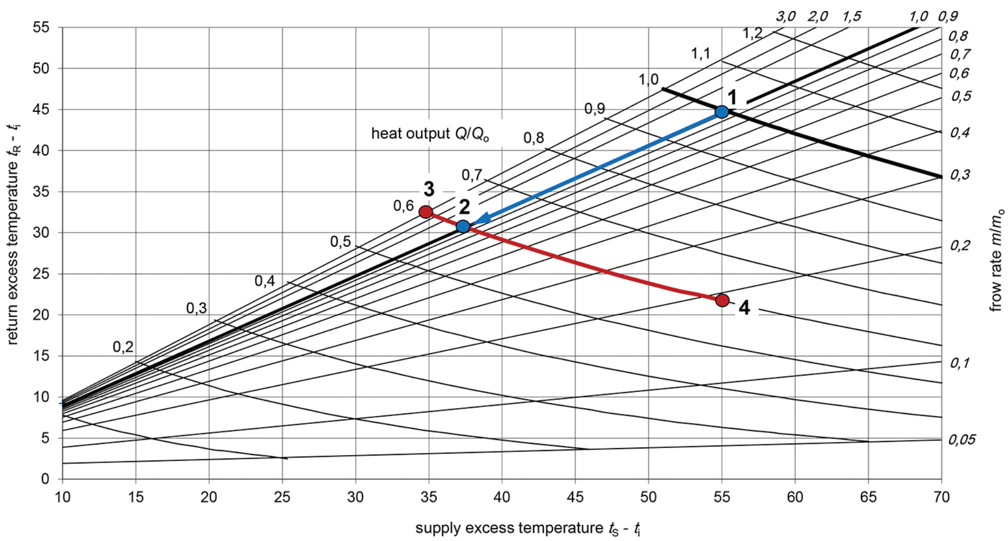

Figure 3. Heat output at reduced heat demand for 40%.

Instead of starting point 1, the required radiator heat output at maintained water mass flow is achieved at temperature operating conditions determined with the previously described procedure. The new state corresponds to the temperature regime 57/51/20 or the mean logarithmic excess temperature 33.9 K. We reach the required heat output with the temperature and mass flow combinations depicted as the red line in **Figure 3**.

Figures 2 and **3** show that a higher flow rate can be necessary despite the lower thermal power of the radiator after the refurbishment (point 3 in **Figures 2** and **3**) or a supply temperature equal or lower to the previous value (point 4 in **Figures 2** and **3**). The dependency between the flow rate and temperature is depicted with a red line between points 3 and 4. Therefore, in the first step, we can determine the boundary conditions, which define optimal operation of the heating system:

- The water supply temperature should be lower or equal to the value before the refurbishment.
- Water flow rate should be lower or equal to the value before the refurbishment.

We can depict the restrictions on the operating parameters of the heating system as constrictions of individual radiator operating parameters. **Figure 4** shows the operating parameters of both radiators. The maximal supply temperature is limited with point 1, whereas the minimal value is limited with point 2.

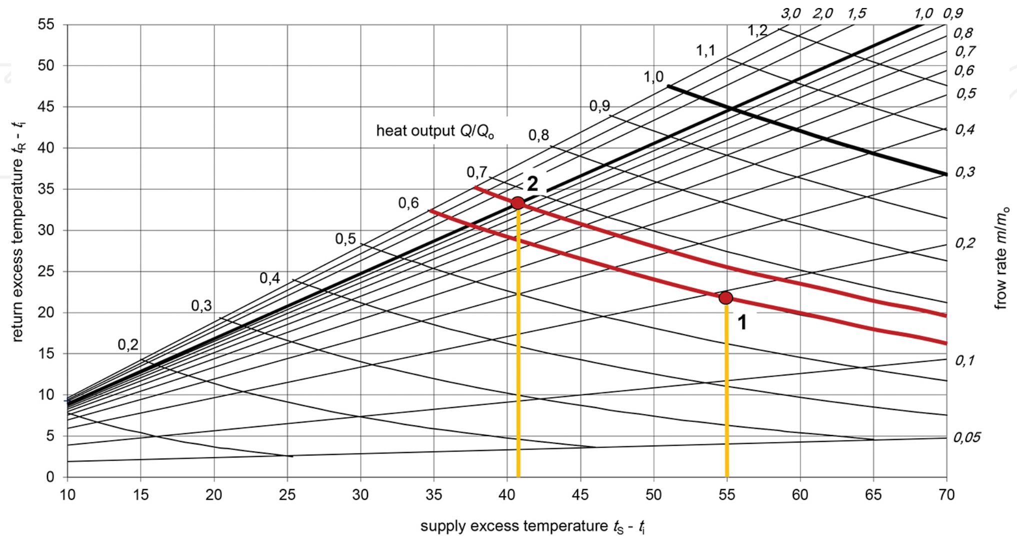

Figure 4. Operating conditions for both radiators after refurbishment.

Since the supply temperature must be equal for all radiators, an intermediate temperature is chosen, e.g., t_S = 65°C. In this case, shown in **Figure 5**, the mass flow for both radiators is determined: $\dot{m}_1 / \dot{m}_0 = 0.37$ and $\dot{m}_2 / \dot{m}_0 = 0.52$.

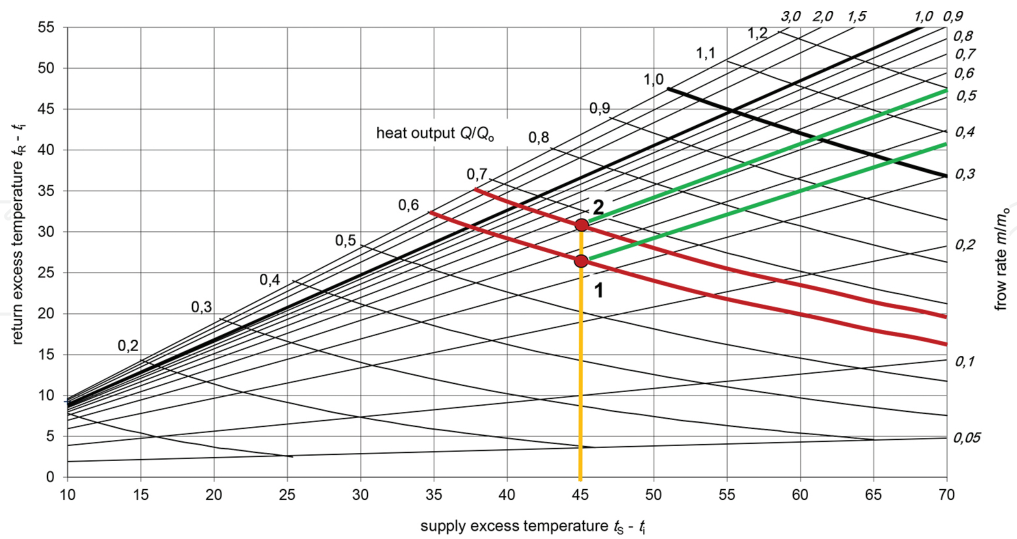

Figure 5. Radiator heat output at a unified supply temperature.

With the heating system temperature, we determine the type of the heat generator or its temperature regime. If we want to use a gas-fired condensing boiler or a heat pump, the required maximal supply temperature is t_S = 55°C. This temperature represents the threshold temperature of the heating system with which we achieve thermal comfort conditions. For heating systems with a lower temperature, a replacement of radiators with other heating element types (fan-coil radiators, fan-coil units), where the heat output does not depend on natural convection, is therefore applicable.

However, in the described example, a supply temperature decrease is possible at the assumption that the critical radiator is replaced. **Figure 6** depicts the case in which the system supply temperature in additionally lowered to t_S = 60°C (yellow line shift on **Figure 6**). The radiators heat output is maintained.

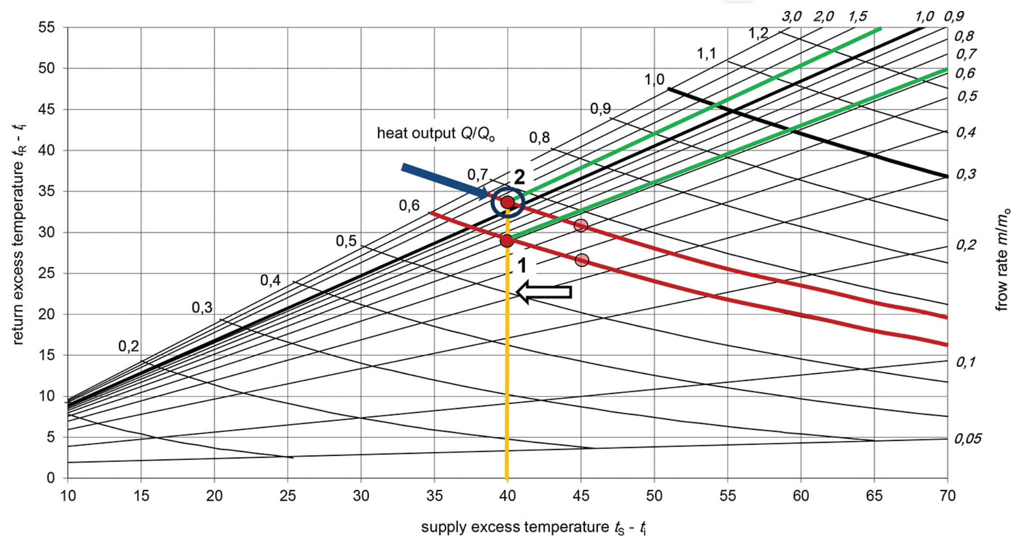

Figure 6. Influence of reduced supply temperature.

Because of the lower supply temperature, a higher water mass flow is required. The required flow rate for radiator 1 is $\dot{m}_1/\dot{m}_0$ = 0.61, which is still lower than the nominal flow rate. For radiator 2 a flow rate of $\dot{m}_2/\dot{m}_0$ = 1.2 is required, which exceeds the base flow rate. We can avoid a higher flow rate in the heating system by replacing the critical radiator with a radiator with a higher nominal heat output.

4. Conclusions

During building retrofit energy use efficiency and cost-effectiveness must also be considered besides the costs. In practice, the retrofit of a building usually consists of a building envelope refurbishment and heat generator replacement. Because of the high cost and the interference in living areas, the heating system (pipping and radiators) is not significantly altered. The envelope refurbishment results in a decrease in the heat required for heating and consequently in the lowering of the required thermal power of the radiators and the heat generator. The lowered thermal power enables the lowering of the heating system temperature regime and

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thereby the option of using a more efficient heat generator. However, heating system efficiency is conditioned with ensuring thermal comfort, which must be met in every case.

In this work, a method for determining the heating system operation conditions is presented. The problem of uneven reduction in the required thermal power of radiators is exposed, which is a consequence of uneven decreases in room heat losses. A larger fraction of outer wall area results in a more significant decrease in the required radiator power in that room. Therefore, new operation parameters must be determined based on the load of individual radiators. The presented method is demonstrated on a case of two radiators with different thermal characteristics.

The influence of radiators on the building system's energy efficiency is taken into account in two respects: with the determination of the whole system's temperature regime and the required mass flow rate. Both parameters are interdependent; thus, parameter optimization is achieved under the consideration of proper boundary conditions. In the demonstrated example, the following conditions were considered: the flow rate must be lower or equal to the existing one—hereby minimal energy use of the circulating pump is assured. The second restriction represents the supply temperature, which must be lower or equal to the existing value, which is a precondition for efficient heat generator operation. The temperature of radiators required to still ensure thermal comfort of the room was also considered. The combination of both parameters ensures optimal and energy-efficient operation of the heating system.

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