Radiators, convectors and energy efficiency

Improving energy efficiency has been a key objective in the construction industry over the last few decades. New energy-efficient features have been sought also for components such as radiators and convectors.

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The suppliers of heat emitters have advertised and promoted positive individual features of the product, like higher heat radiation, lower back wall losses and quicker response to control. But this is not that simple: energy efficiency is associated with the heating process and therefore the matter has to be seen in the whole, not as a sub-optimization of the details.

There are of course differences between different radiators and convectors, but the question is, what are the differences in terms of comfort, energy efficiency and in the end money?

The purpose of this article is to provide answers to these essential questions with objective measurement-based information.

The considered heat emitter types and relevant aspects

In **Figure 1**, the considered heat emitter types are illustrated.

For comparison of the heating process in buildings, following functions of heat emitters are essential:

- Human response to the heat emission
- Heat radiation into the room
- Back wall heat losses
- Temperature control function
- Heat output capacity at partial loads
- Influence on heat generation

Secondary and from the comparison perspective unimportant items like heat storage and distribution (pipe work) losses as well as other control methods have not been taken into consideration in this review.

Main part of the measurement results referred to in this article are from laboratory tests performed by Dr. Konzelmann at the WTP GmbH Berlin (**Figure 2**) and from the analysis done by Professor Kurnitski and his team at the Tallinn University of Technology as well as from our in-house analysis [1].

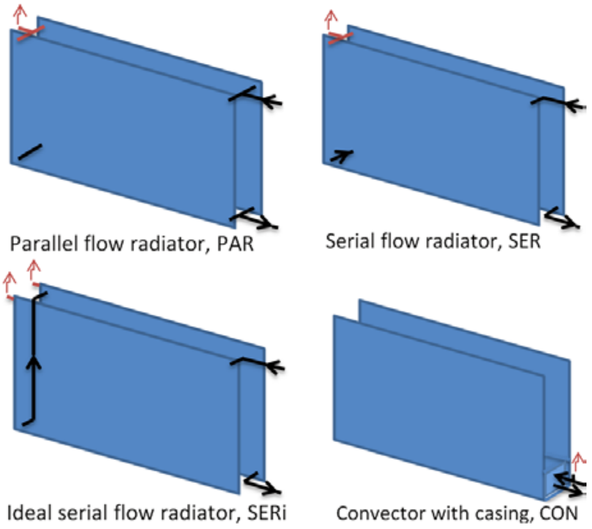

Parallel flow radiator, PAR
Serial flow radiator, SER
Ideal serial flow radiator, SERi
Convector with casing, CON

Figure 1. Investigated heat emitters: Normal 2-panel radiator with parallel flow (PAR), typical 2-panel radiator with serial flow (SER), ideal 2-panel radiator with serial flow (SERi), conventional round tube/lamella convector with or without casing (CON) and ideal convector (CONi) like trench convector (not illustrated). ↑ = Air bleed.

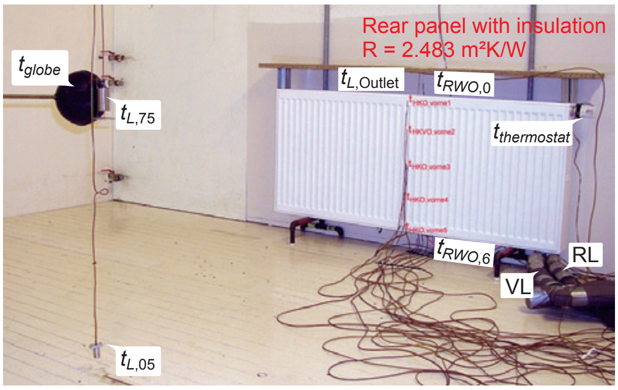


Figure 2. Measurement set up at the WTP GmbH Berlin lab.

In laboratory measurements, we wanted to find out how a normal 2-panel radiator (PAR) and a typical 2-panel radiator with serial flow (SER) behave under the control of a thermostatic radiator valve under comparable conditions. Conclusions of the ideal 2-panel radiator with serial flow (SERi), conventional convector (CON) and ideal convector (CONi) function can also be drawn with sufficient accuracy from the measurement results.

Human response to the heat emission

Humans are to detect small and rapid temperature variations in their environment. Up to 0.1 degrees step changes at operative temperature are measured in our own experimental tests. Instead, slow temperature changes, less than one degree in 15 minutes [2], are not perceived, because the human body's own heat regulation system is able to adapt to that change under normal conditions. This provides an explanation why we do not experience a problem, when the thermostat regulates the radiator water flow and the radiator temperatures shift correspondingly.

The best location of the radiator is beneath the window where it blocks the downdraught, the convection flow from the cold window surface. Another important feature of the radiator is its thermal radiation, which compensates for the radiant effect of the colder window surface, creating the conditions for thermal comfort. In fact, the radiator beneath the window extends the usable interior space.

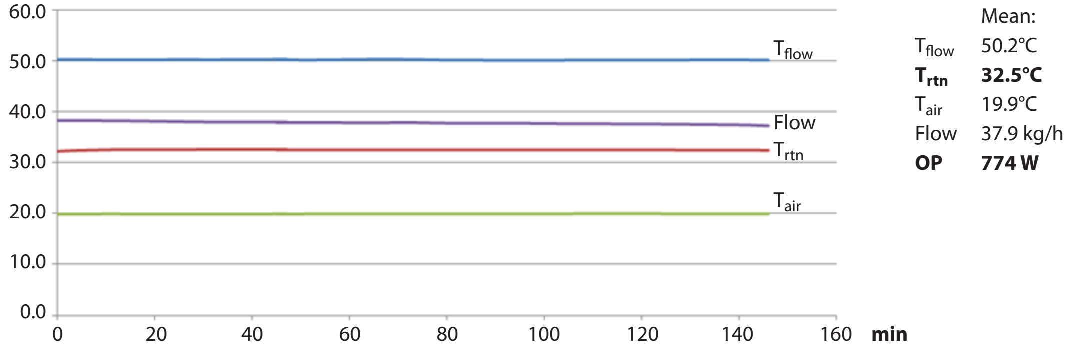
Emitter temperatures and heat losses

Measurements at 75% part load conditions [3]

The 75% part load means that the free heat gain rate is 25%. The free heat gains consist of internal heat gains and solar radiation influence. The average cabin cooling effect was 774 W. Flow temperature was set on 50°C. Thermostatic radiator valve TRV was a conventional proportional one and water flow rate lowered to a level of around 1/3 $\dot{m}_N$, where the PAR radiator heat output was in balance with the heat demand. Differential pressure was kept constant in all measurements. Nominal flow rate, $\dot{m}_N$, is the flow value of the radiator measured in the EN 442 conditions and temperatures flow = 75°C, return = 65°C and air = 20°C.

As shown in **Figure 3**, The main observations of the test results are that the SER had around 15% lower heat output capacity than PAR and resulting to a 26% higher flow rate and to around 3.7°C higher return water temperature. SER got also an average front panel temperature of 4.5°C higher and 2.5°C lower average rear panel temperature than the PAR ones.

Average 301 and 303: Parallel – Part load 75%



Average 101 and 103: Serial – Part load 75%

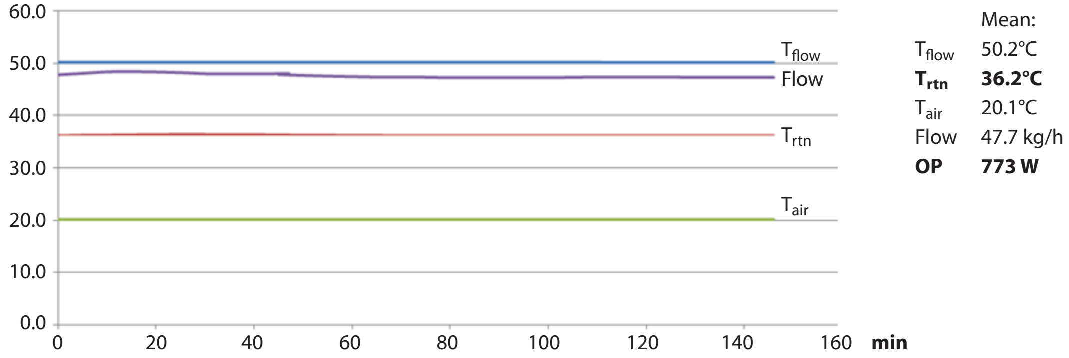


Figure 3. PAR and SER running with TRV control at 75% part load conditions.

Theoretically, the SERi heat output capacity could be a bit higher than SER although own laboratory measurements of a commercial product did not confirm this difference [1]. Obvious is that SERi gets at same conditions practically the same flow rate and return temperatures as PAR. Due to the lower flow rate than SER at these conditions the front and rear panel temperatures are slightly lower than the SER ones. For comparison purposes (**Table 1**) we can well approximate the SERi panel temperatures: the front 4.0°C higher than the PAR one and the rear respectively 3.5°C lower than the PAR one. Convector features are handled in the later part of this review.

Table 1. 75% part load measurement results.
* Estimated value

T_{flow} = 50°C T_{air} = 20°C Φ_{cool} = 774 W	T_{rtn} °C	T_{front} °C	T_{rear} °C
PAR	32.5	39.1	40.1
SER	36.2	43.6	37.6
SERi	32.5*	43.1*	36.6*
CON	–	–	–
CONi	–	–	–

Panel radiator heat output capacity depends not only on the temperatures, but also on the flow rate and the pipe connection. Radiators with top-bottom-same-end (TBSE) as well as top-bottom-opposite-ends (TBOE) connections are not so sensitive to the water flow rate changes that bottom-bottom-opposite-end (BBOE) connections are. This function is shown in the redrawn graph of Schlapmann [4], **Figure 4**. Here we can also see the reason why SER has a reduced heat capacity: the SER rear panel is connected as BBOE and the heat capacity is clearly lowered at smaller water flow rates. – **Increased SER radiator sizes are needed.**

Measurements at 42% part load conditions [3]

A 42% part load means that the heat gains cover 58% of the heat demand. Measurements were carried out with an average cabin cooling effect of 875 W and flow temperature of 70°C in order to get well-measurable function values.

Thermostatic radiator valve TRV starts to reduce the water flow to the level on which the radiator heat output corresponds with the heat demand. The proportional control is no longer reached and the control mode starts to fluctuate as on-off. Water flow shut-off time is around 30% of the on-off cycle, however, with PAR a bit longer than with SER.

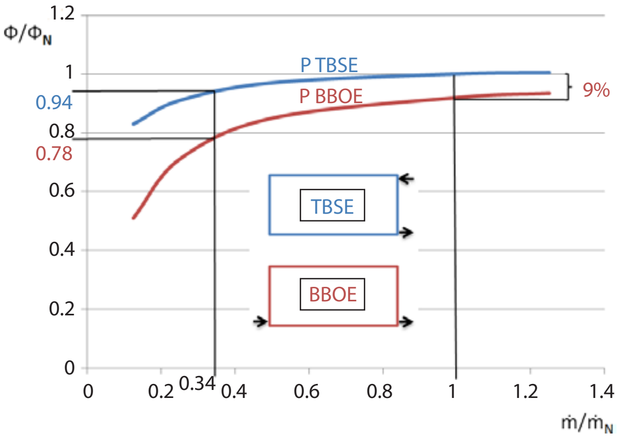


Figure 4. Panel radiator heat capacity depends also on flow rate and connection type.

Temperature control function

At start phase of the fluctuation both temperatures, air and globe, react a bit quicker with PAR than with SER, due to the higher output capacity of PAR, **Figure 5**. However, this difference equalizes due to the fact that **TRV determines the pace**: During regular fluctuation both radiators PAR and SER have the same cycle time, **Figure 6**. And that is why there are no practical differences in the controllability of radiators. Convectors may benefit slightly from the reduced output capacity at high heat gain rates and the shut-off time can be shorter. This feature is described in the chapter *Return water temperature influence*.

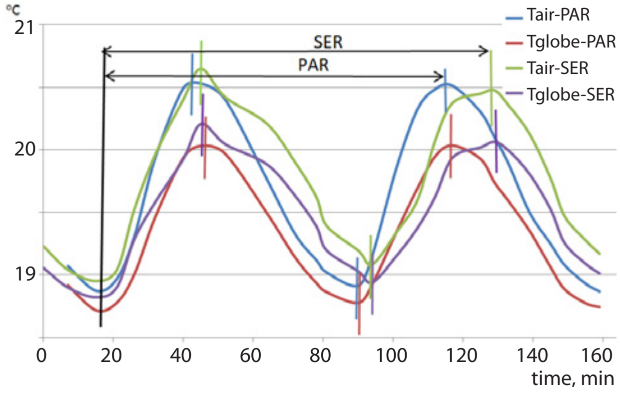


Figure 5. PAR heats up the room slightly quicker than SER.

Due to the insufficient differences at on-off modes, the temperature fluctuation impact on the energy use has not been taken into consideration in this article (generally it depends on the control used).

Water flows fluctuate between 0 and 60 kg/h. Flow-rate-weighted average return temperatures of SER were 2.1°C higher than the PAR ones. Front panel mean temperature of SER was 5.3°C higher than PAR. Rear panel mean temperature was correspondingly 3.2°C lower for SER.

Condition for a PAR (radiator type 22-600-1400), where T_{flow} = 70°C and T_{rtn} = 32°C with continuous flow, in other words TRV is still in proportional mode, corresponds to the heat gain rate of 35%. Obviously the TRV can modulate the flow up to this 35% heat gain rate and at higher heat gains the TRV changes over to on-off operation. Corresponding SER values and estimated SERi values are shown in **Table 2**.

Norm and old building

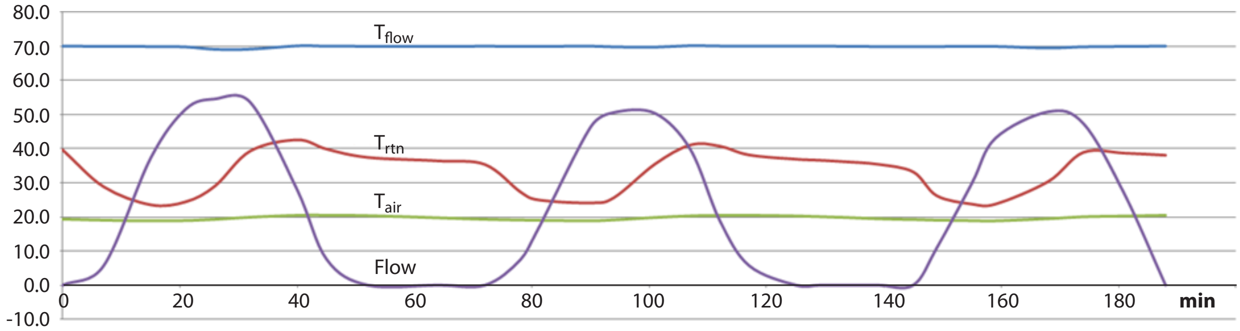
For comparison purposes two different building types have been selected, old and norm: A post WWII building without thermal insulations layers in the walls, but 2-glass-windows and a norm building representing both newer building types, from the 90s, and renovated older buildings. Old and norm building features displayed in **Table 3** have been used for calculations.

Table 2. 42% part load results.*Estimated value

T_{flow} = 70°C T_{air} = 20°C Φ_{cool} = 875 W	Weighted T_{rtn} °C	T_{front} °C	T_{rear} °C
PAR	32.1	40.3	40.7
SER	34.2	45.6	37.5
SERi	32.1*	45.1*	36.5*
CON	–	–	–
CONi	–	–	–

Table 3. U-values of reference buildings

	External wall U-value	**Window U-value**
Old building	1.39 W/m²K	2.8 Wm²K
Norm building	0.27 W/m²K	1.2 W/m²K


302 – Parallel: Mean output 873 W, flow rate weighted average return temp 32.1°C, part load 42%

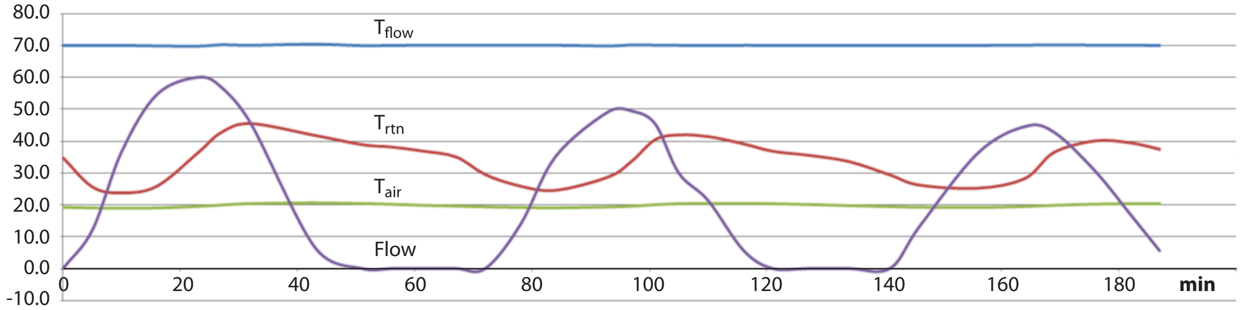

102 – Serial: Mean output 878 W, flow rate weighted average return temp 34.2°C, part load around 50%

Figure 6. PAR and SER running with TRV control at 42% part load conditions. On-off-mode.

Climate conditions are taken according to Dresden (Germany), where the design outdoor temperature is -15°C.

Outdoor temperature of 0°C has been chosen as reference, because it is reasonably near to the mean temperature of the heating season.

Reference room is 16 m², window 1.4 x 1.5 m² and heat emitter size 1.4 x 0.6 m². Heating system design temperatures are 70/55/21°C for old building and 55/45/21°C for norm building. System flow temperatures at T_{out} = 0°C are in old building 50°C and in norm building 41°C. Air change rate is 1/h in both cases. Full load heat demands are in the old building 890 W and in the norm building 420 W. Heat gain rates are at these conditions in old building 25% and in norm building 35%. Default is that at both conditions the TRV works in proportional flow mode.

These conditions are chosen in order to show the maximum differences between the heaters. However, in practice the differences are smaller.

With help of the conversion graph in **Figure 7**, based on the measured temperatures, it is possible to estimate the average panel temperatures from the flow and return temperatures of radiator (**Table 4** and **5**).

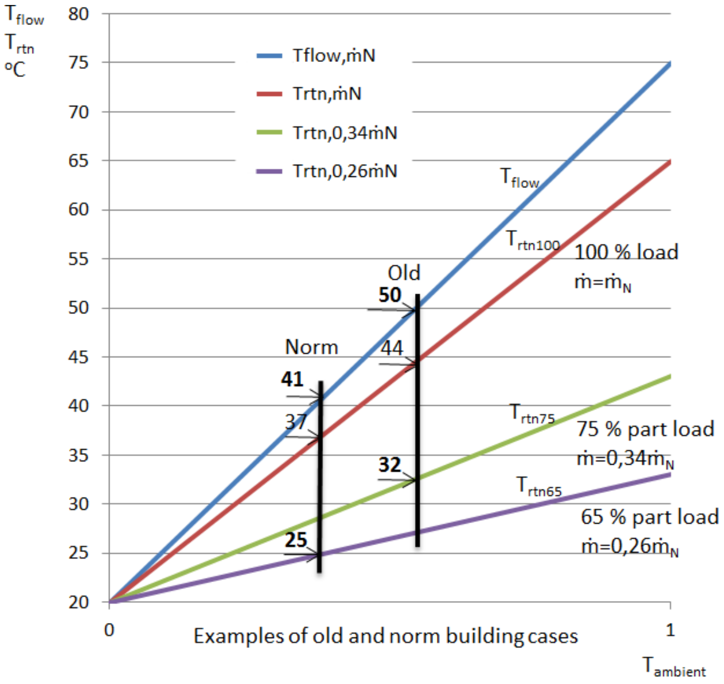


Figure 7. Radiator temperatures of PAR and SERi in relation to the flow temperature and the part load rate.

Table 4. Radiator surface temperatures, old building. *Selected value

Old building	PAR	SER	SERi	CON	CONi
Front panel mean, °C	39.1	43.6	43.1	31*	–
Rear panel mean, °C	40.1	37.5	36.6	31*	–

Table 5. Radiator surface temperatures, norm building. *Selected value

Norm building	PAR	SER	SERi	CON	CONi
Front panel mean, °C	28.0	31.0	29.8	25*	–
Rear panel mean, °C	28.2	27.0	26.5	25*	–

Operative temperatures

Based on these average front panel temperatures it is possible to calculate the heat radiation influence according to ISO 7726 standard. Measurement point is in the middle of the room at 0.6 m above floor level, referring to a person in a sitting position. These calculations are made by Equa Simulation Finland Oy [5].

There is no standardized calculation method for energy estimations, but the following calculation method, mean operative temperature MOT, is commonly used. In **Tables 6** and **7** are the calculated air temperatures giving the same operative temperatures of 21°C at different heat emitter cases. SER shows the lowest air temperature due to the highest radiation and CONi respectively the highest. SERi is quite similar as SER.

Table 6. Air temperatures giving the same 21°C MOT, old building.

Old building	PAR	SER	SERi	CON	CONi
Air, °C	21.38	21.26	21.27	21.59	21.90

Table 7. Air temperatures giving the same 21°C MOT, norm building.

Norm building	PAR	SER	SERi	CON	CONi
Air, °C	21.14	21.05	21.06	21.21	21.32

Heat radiation influence

Reference location Dresden's design outdoor temperature for heating is -15°C. Climate data for the calculations is taken from the Weather Underground.

Degree-day value of the old building with base temperature 17°C is 2902 and the difference of one degree corresponds with 10% difference in energy use.

Norm building degree-day value with base temperature 15°C is 2354 and the difference of one degree corresponds with 12% difference in energy use.

Tables 8 and **9** show how much operative temperature differences (**Tables 6** and **7**) add to energy needs of different emitter types.

Table 8. Heat radiation influence in old building.

Old building	SER/SERi	PAR	CON	CONi
Additional energy	0	+ 1.2%	+ 3.3%	+ 6.4%

Table 9. Heat radiation influence in norm building.

Norm building	SER/SERi	PAR	CON	CONi
Additional energy	0	+ 1.0%	+ 1.8%	+ 3.1%

Back wall losses

From the measurement results of WTP GmbH Berlin it is possible to calculate, with good degree of accuracy, the back wall heat losses caused by the heat emitter, see **Table 10, 11** and **12**.

Table 10. Emitter back and back wall temperatures in old building. *Selected value

Old building	PAR	SER	SERi	CON	CONi
Emitter back mean, °C	40.1	37.5	36.6	31*	–
Back wall mean, °C	29.5	28.1	27.6	24.7	–

Table 11. Emitter back and back wall temperatures in norm building. *Selected value

Norm building	PAR	SER	SERi	CON	CONi
Emitter back mean, °C	28.2	27.0	26.5	25*	–
Back wall mean, °C	23.3	22.6	22.4	21.6	–

Table 12. Back wall losses caused by the heat emitter.

Additional energy need	PAR	SER	SERi	CON	CONi
Old building	+2.24%	+1.91%	+1.79%	+1.10%	–
Norm building	+0.36%	+0.28%	+0.26%	+0.18%	–

Following the back wall temperature values the radiator back wall losses can be calculated at outdoor temperature of 0°C.

Influence of leak flow on serial panel radiators

Bleeding of the air is a problem at construction of the serial panel radiators. In order to get the serial panel radiator to function ideally, both panels, front and rear, should be bled separately. To enable this, complicated air venting arrangements are needed. Therefore, the product costs will increase.

All commercial SER products are compromised by having a tiny opening between the front and rear panels. This helps to bleed the air through the same air vent at the upper end of the radiator, but it inevitably leads to a leak flow from front panel to rear panel resulting in a situation, where the top of the rear panel is warmer than the flow water from the front to back panel. This prevents the water rising up in the rear panel, which causes an additional reduction on the output capacity of the rear panel particularly at the part load conditions. This has been found in the measurements [3].

The leak flow in SERi radiator reduces also the output capacity and equalizes the front and rear panel temperatures. However, the disadvantage is not as serious as in SER radiators.

Serial panel radiator has an increased flow resistance. When parallel panel radiator resistance corresponds with around kv 3.3, serial panel resistance is more than the double, kv 1.3. The pressure difference between the panels can be a few hundred Pascal even in normal sizes of serial radiators and the leak flow through even smaller openings is unavoidable.

Return water temperature influence on heat generation

As shown in **Figure 4** panel radiator output capacity depends also on the connection type and flow rate. We can recognize that SER radiator's rear panel connection is BBOE type and thereby SER radiator capacity is always smaller than the PAR one. In addition, the leak flow reduces the output capacity further.

As mentioned above in the 75% part load case, the return water temperature of SER radiator was measured 3.7°C higher than in the PAR. Also, in the 42% part load case this reduction was remarkable – the higher return water temperature, the higher the condensing boiler and heat pump fuel consumption.

Heat output capacity of convectors with round pipe/lamella construction depends strongly on the water flow type, turbulent or laminar. When the flow rate is decreased, the convector output capacity decreases in accordance with the Reynolds number. This dependence, according to Dr. Konzelmann [3], is shown in **Figure 8**.

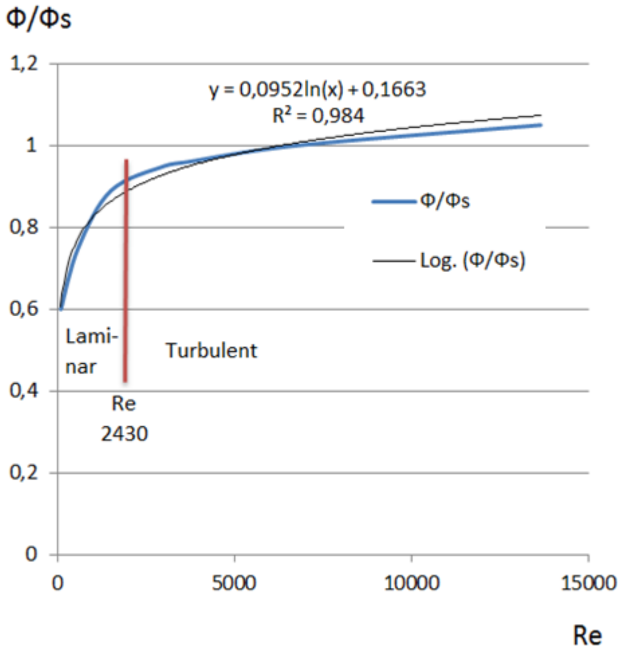


Figure 8. Convector heat output depends on water flow conditions

Example: Typical convector construction with heat output capacity at dT50K (EN442) is 800 W. In case of 75% part load, flow temperature of 50°C and 248 W heat demand, the return water temperature rises up to a level of 39°C.

- Comparable case, PAR radiator with a return water temperature of 33°C.

Note. This heat output capacity reduction effect has not been taken into account in the product standards EN442 and EN16430: standard heat output values are valid only at full load conditions with relatively high water flow rates. Design flow rates are often clearly lower, which leads to incorrect design selections.

In **Figure 9** we can find, according to Professor Oschatz's measurement and study [6], the dependence of heating system return water temperature on the condensing gas boiler combustion efficiency: trend line value 0.4%/K. The burner load rate has also a slight influence on the efficiency: the lower load the higher efficiency and respectively the higher load the lower efficiency.

Annual coefficient of performance, COPa, is also linked not only to the system flow water temperature, as often assumed, but also to the system return water temperature. According to the calculations done the change of one degree in system water temperature gives a COPa change of 1.2% [8]. In addition, the COP value depends on the heat pump condenser temperature. It is also measured that the system flow water temperature has a 2/3 and system return water temperature a 1/3 influence to the condenser temperature, **Figure 10**.

In conclusion, we can say that in both condensing boiler and heat pump, lowering the system return water temperature by one degree, the heat generation efficiency rises by 0.4%.

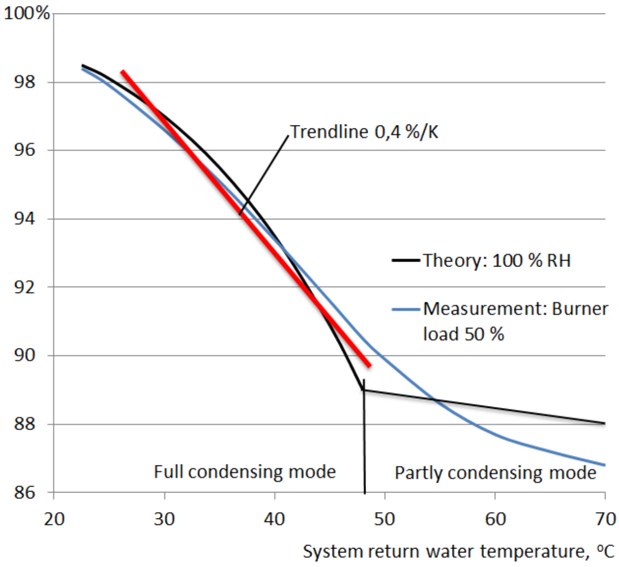


Figure 9. Condensing boiler combustion efficiency depends on system return water temperature

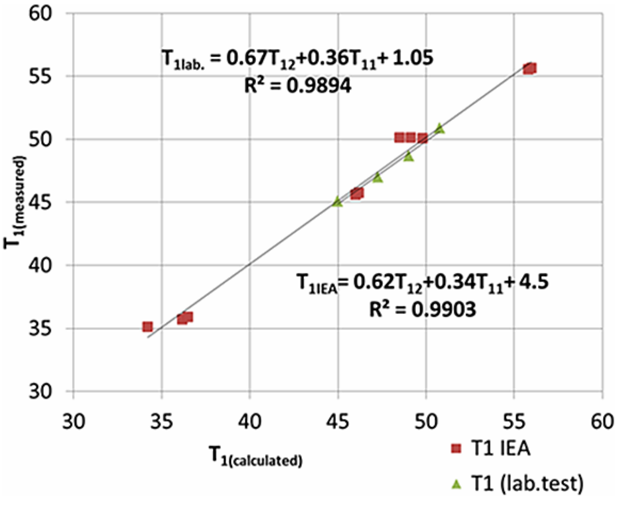


Figure 10. Influence to heat pump efficiency, Prof. Kurnitski [7]. Flow water temperature 2/3 and return water temperature 1/3.

When using the return water temperatures from the 75% par load case, SER has 3.7°C higher return water temperature than PAR and SERi, and CON and CONi respectively around 6°C higher than PAR and SERi, following figures for **heat generation efficiencies** can be calculated, **Table 13**. These values are valid for both reference buildings with a reasonable accuracy.

Table 13. Relative heat generation influence and additional energy needs.

Heat generation influence	PAR/SERi	SER	CON/CONi
Additional energy	0	+1.5%	+2.4%

Summary

Table 14 shows a collection and summary of the relative effect of different heat emitters on the heating system efficiency: additional energy need.

Table 14. Relative effect of different heat emitters on system efficiency

Additional energy need	PAR	SER	SERi	CON	CONi
Old building	+3.4%	+3.4%	+1.8%	+6.8%	+8.8%
Norm building	+1.4%	+1.8%	+0.3%	+4.4%	+5.5%

Discussion

According to the results differences between the radiators in both old and norm buildings are very small, max 1.5%. However, the convectors differ clearly from the radiators.

Heat radiation differences of different radiator types are so small that they are practically out of human perception capability [9].

When the functional differences between the radiators are small, the decisive difference is their price. But how much more money is meaningful to invest in radiators that are claimed to be more energy-efficient?

Example: In a typical German detached house of 170 m² from the mid-90s the space heating energy is around 15 000 kWh per year. When using the gas price of 0.065 €/kWh, the heating bill is around 975 €/a. The result difference between a “standard radiator” and an “ideal serial panel radiator” is 1.1%. The corresponding energy cost difference is on average 10.70 €/a. This divided typically into 10 radiators results in maximum annual savings of 1.07 € per radiator. For instance, the price of an “**ideal serial panel radiator**” for the end user is several dozens of euros higher than the price of a standard radiator. This extra price, for example **30 €** for the end user, divided by 1.07 €/a leads to a pay-back time of 28 years!

The reduced heat output capacity of the “**typical serial panel radiator**” causes needs to increase the radiator size: for example, a typical 10% addition increases the price for the end user by around **25 €,** and this without any pay-back.

The additional heating energy demand and the lack of radiant effect of convectors seem to be more noticeable: there must be additional arguments for convector selection.

In modern energy efficient buildings, which are better insulated and often equipped with heat recovery ventilation, the heating energy demand is only half or less of the “norm building” used in this review. Therefore, the small differences of radiators in new buildings are completely irrelevant from the energy saving point of view.

In conclusion, it is clear that there is no tangible, financial nor physiological benefit for home owners to pay the increased cost associated with the alleged but unsubstantiated “more energy efficient radiators”. **– A standard radiator is the best option.** ■

References

[1] RETTIG ICC Research Centre, EN442 laboratory.

[2] ASHRAE ANSI standard 55.

[3] WTP GmbH Berlin, EN 442 laboratory.

[4] Schlapmann, HLH 9-76.

[5] Equa Simulation Finland Oy.

[6] Technical University of Dresden.

[7] Tallinn University of Technology.

[8] IVT VPW2100 software.

[9] Human Thermal Model, VTT Technical Research Centre of Finland.