Vertical temperature gradients in apartments with hydronic radiator heating

Mats Dahlblom[1], Birgitta Nordquist[1], Petter Wallentén[2], Lars-Erik Harderup[2] and Lars Jensen[1].

[1] Building Services, Department of Building and Environmental Technology, LTH, Lund University, Sweden
[2] Building Physics, Department of Building and Environmental Technology, LTH, Lund University, Sweden
Mats.dahlblom@hvac.lth.se

Abstract. A vertical temperature stratification normally exists in rooms during the heating season in cold climates. An expression of the gradient in apartments heated by hydronic radiator heating systems with exhaust ventilation has earlier been developed assuming a dependency of the outdoor temperature. The expression was used by a public real estate owner when re-calculating measured indoor temperature at 2.1 m above floor to 1.2 m above floor representing the occupancy zone and used for individual metering and billing of space heating cost. To validate the suggested expression temperature measurements have been made at four heights in living rooms in apartments built in the 70's. The heights includes 0.0, 0.1, 1.1 and 1.7 m above floor. The theoretical expression has been compared to the full-scale measurements and in general the expression overestimates the vertical temperature gradient. The measured gradients are generally very low. The thermal comfort in the aspect of vertical temperature gradient is good for the studied period.

Keywords: Vertical temperature gradient. Indoor temperature. Residential apartments. Hydronic heating system.

1 Introduction

A vertical temperature stratification usually arise indoors. The pattern of this gradient depends during the heating season on the type of heating system, and the characteristic of the surrounding surfaces and the type of heat sources inside the room. The type of ventilation system will also influence the temperature distribution in the room. The vertical gradient is important for thermal comfort aspects, a too high temperature difference may negatively affect the thermal comfort experience.

The gradient is also important in aspects of controlling the heating system. The feed forward control method used for hydronic heating system that has been applied for many years only account for the outdoor temperature. This may result in too high room temperatures and unnecessary energy use during for example sunny days. It may also lead to increased airing resulting in increased energy use. The feed forward control method has drawbacks both in terms of thermal comfort and energy use.

An improved control method; the feed-back method which also accounts for the heat gains and losses inside the rooms has however during the recent years been given more focus. There has been successful implementations of this method in real apartment buildings [1]. The results show a decreased correlation to the outdoor temperature and a more even indoor temperature which is the purpose of the method. If some form of feed-back control is to be applied the indoor temperature must be measured in order to control the supply temperature of the hydronic heating system. As the temperature varies in height, the height of a reference temperature sensor inside a room is also of significance for the outcome of the control and thereby the resulting indoor temperature in the room. This will influence both the thermal climate in the rooms and possibly also the energy use for space heating.

So consequently it is important for both thermal comfort and energy use to have knowledge about the vertical temperature gradient inside rooms.

Overby et al [2] present a model for calculation of vertical temperature gradient in a room heated by an electrical radiator and without forced air movement. The plume generated by the radiator has in the model been calculated from an equation for a linear heat source also presented in Hansen et al [3]. The model and the laboratory measurements presented in [2] agrees well for a case with a heat load of 400 W, in which the gradient varies from approximately 0.5 K/m at start to approximately 1.5 K/m after 8 hours with this heat load.

Laboratory studies on temperature gradients in rooms can be found, several of them concern rooms with displacement ventilation. Studies with full-scale measurements in real buildings are however limited. One study explores the vertical temperature gradient for a multi-storey building [4]. This investigates how vertically adjacent apartments thermally influence each other. The present study focus on vertical temperature gradient in occupied apartments with radiator heating and mechanical exhaust air ventilation.

In southern Sweden a municipal company has introduced a feedback control method. In the actual buildings a system for individual measuring and billing of space heating costs (IMB) was in place [5]. In this system temperature sensors were placed in every living room and every bedroom. The sensors are mounted just above the doorframe, i.e. 2.1 m above floor on inner walls, not to be blocked by furniture or disturbed by solar heat or internal heat sources. Though, this level is above the occupancy zone, and to get a more fairly value corresponding to the thermal comfort the temperature has been re-calculated to a temperature at 1.2 m height above floor with respect to the vertical temperature gradient with a proposed equation based on linear heat sources. This temperature has then been used as the reference temperature used for billing in the IMB system. Some comparing measurements have been made by Rundberg [6], but the equation used for this recalculation needs to be validated in a more extensive way.

It is also, as mentioned, important to know about the vertical temperature gradient for thermal comfort reasons. Temperature measurements have been performed in apartments owned by the company in a large multi-disciplinary research project called

PEIRE [7]. The overall purpose of that project is to examine the indoor climate and energy use before and after renovation as well as resident behaviour related issues. The performed measurements before the renovation allows validation of the suggested equation as well as serving reference values for vertical temperature gradients that could be expected in occupied apartments.

The purpose of the paper is to examine whether the proposed equation for vertical temperature stratification coincides with temperature gradients in apartments and also attain reference values of temperature gradients in apartments heated by a hydronic system with radiators in each room and ventilated by a mechanical exhaust system with air intake terminals through the façade.

2 Methods

2.1 Proposed equation of vertical gradient in apartments heated by hydronic heating

When introducing individual metering and billing of space heating costs, the indoor temperature was for practical reasons measured at a height of 2.1 m. An expression for estimating the vertical temperature gradient in an apartment were developed to be able to estimate the temperature at 1.2 m. This was done to attain more representative values for the thermal comfort in the apartments as 1.2 m is included in the occupancy zone and 2.1 m is not. If the billing were to be based on the measured value at 2.1 m the temperature could be overestimated, knowing that a vertical gradient exists, which could imply that the residents would be paying a too high cost for the space heating.

The indoor temperature was, due to an assumed vertical temperature gradient, recalculated to 1.2 m above floor with the equation.

$$T_i = T_{meas} - 1 + 0.025 \cdot T_e \qquad (1)$$

T_e external (outdoor) temperature (°C)
T_i mean indoor temperature (current value) 1.2 m above floor (°C)
T_{meas} measured room temperature at 2.1 m above floor (°C)

At an outdoor temperature of 0°C the expression gives 1°C lower temperature at 1.2 m compared to 2.1 m above floor level, i.e. a vertical temperature gradient of 1/0.9 = 1.11 K/m.

The expression is developed based on theories of temperature gradients created by one or more punctiform heat sources and by a linear heat source [3], field measurements in seven residential apartments during the implementation of a measurement system aimed for individual measuring and billing (IMB) of space heating costs and complementary field measurements in two different apartments [6].

The result from [6] was that the vertical temperature gradient varied from approximately 0.5 K/m at no heat load to 1.5 K/m at large heat loads. If the heat load are distributed on more than one source the gradient will be lower. In a room there normally is more than one heat source, except from the radiator there are electrical appliances, persons and insolation.

2.2 Temperature measurements in apartments during heating season

Temperature measurements have been made in ten apartments during the heating season between the 16th of January and 5th of April 2017. The same equipment has been used moving it between the apartments. The measurement period has been daylong, i.e. both days and nights, one week in each apartment, starting in apartment 1 then moving to number 2 on the same day, for a total of ten weeks. Three gradients have been measured in each apartment; one in the master bed room and two in the living room; one closer to the exterior wall and windows and one in the inner part of the room, Table 1. HOBO loggers (HOBO U12-012) with accuracy of ± 0.2°C were used and external temperature sensors (TMC x-HD) mounted inside a black painted spherical globe [8].

Table 1. Sensor type and placements.

Height above floor/Room	0.0 m	0.1 m	0.6 m	1.1 m	1.7 m
Living room inner	Logger	Globe	---	Globe	Logger
Living room façade	Logger	Globe	Logger	Globe	---
Bed room façade	Logger	Globe	Logger	Globe	---

The outdoor temperature was measured at a location 2.5 kilometers from the buildings.

The buildings consist of three story rectangular concrete buildings with infill walls of wooden studs with filling of mineral wool. Each building contains 20 – 25 apartments distributed on three stairwells. The buildings are ventilated by a mechanical exhaust ventilation system. The outdoor air is supplied directly to the bed rooms and living rooms through vents and extracted in kitchens and bathrooms.

3 Results

Measurements were performed in ten apartments, from which preliminary results are presented for apartment no. 3, 5, 6, 8, 9 and 10. Short facts about these are presented in Table 2. The outdoor temperature varied during the measurement period, 2017-01-31—2017-04-05, between -3°C and +20°C.

The temperatures are registered every 5th minute and the differences are calculated for hourly mean values. Based on the temperature difference between sensors at two levels have three different vertical temperature gradients been calculated (A: 0.0-1.7 m, B: 0.1-1.7 m and C: 1.1-1.7 m).

Table 2. Short facts about the apartments.

Apt no.	Size	Apartment type	Living room orientation
3	4 rooms and kitchen	Double-sided	South
5	3 rooms and kitchen	Double-sided	South
6	3 rooms and kitchen	Double-sided	South
8	2 rooms and kitchen	Single-sided	South
9	4 rooms and kitchen	Double-sided	North
10	2 rooms and kitchen	Double-sided	South

Figure 1 – Figure 6 present the calculated vertical temperature gradient (K/m) compared to three gradients (A, B and C) as a function of outdoor temperature. As can be seen the conformity between calculated and measured temperature gradient is weak, except for apartment no. 8, where it is remarkably good if calculated between 1.1 and 1.7 m above floor.

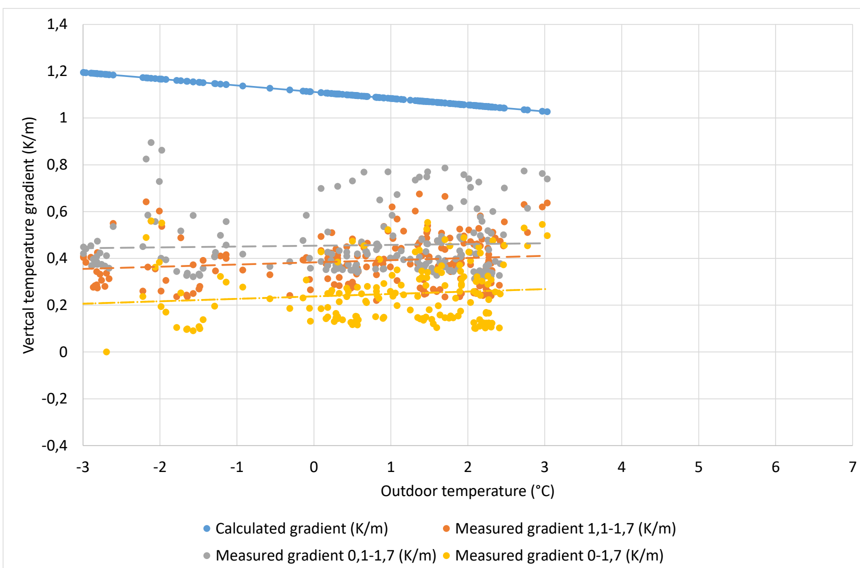

Fig. 1. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 3. 2017-01-31—2017-02-08.

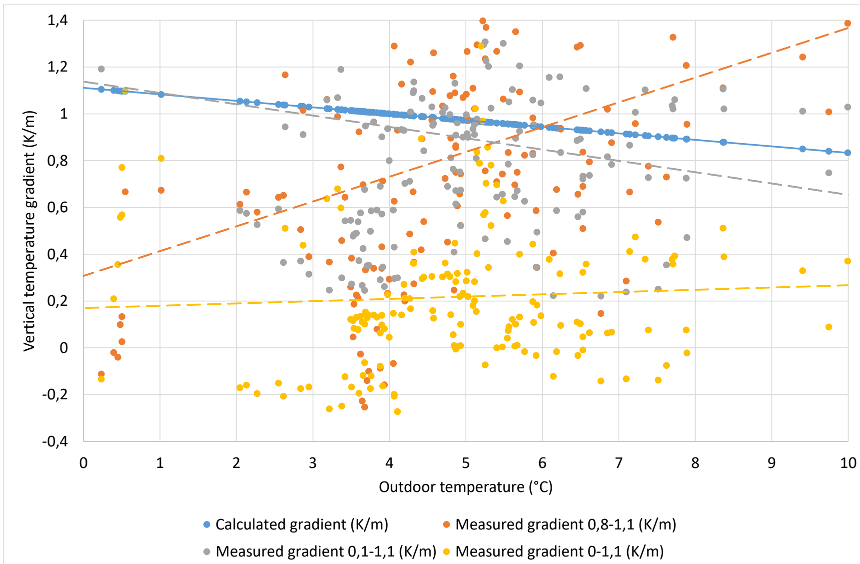

Fig. 2. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 5. 2017-02-16—2017-02-24.

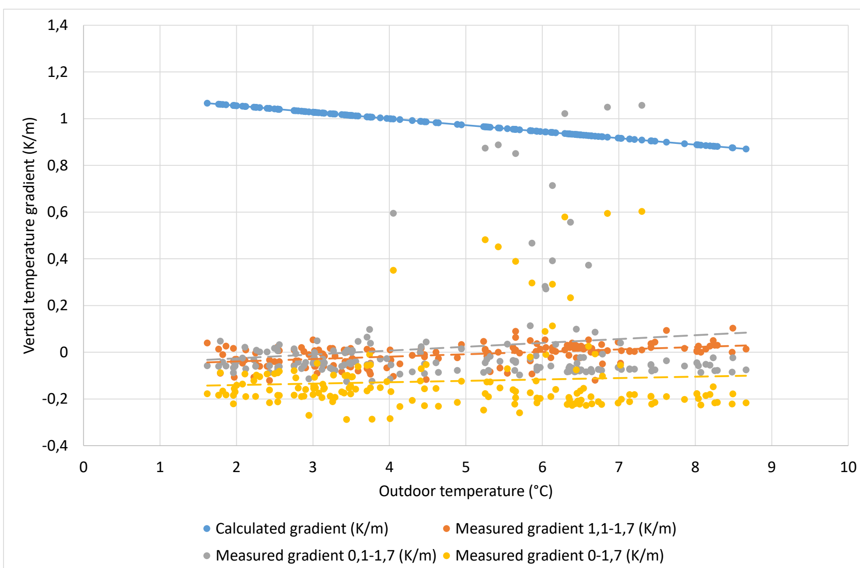

Fig. 3. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 6. 2017-02-25—2017-03-04.

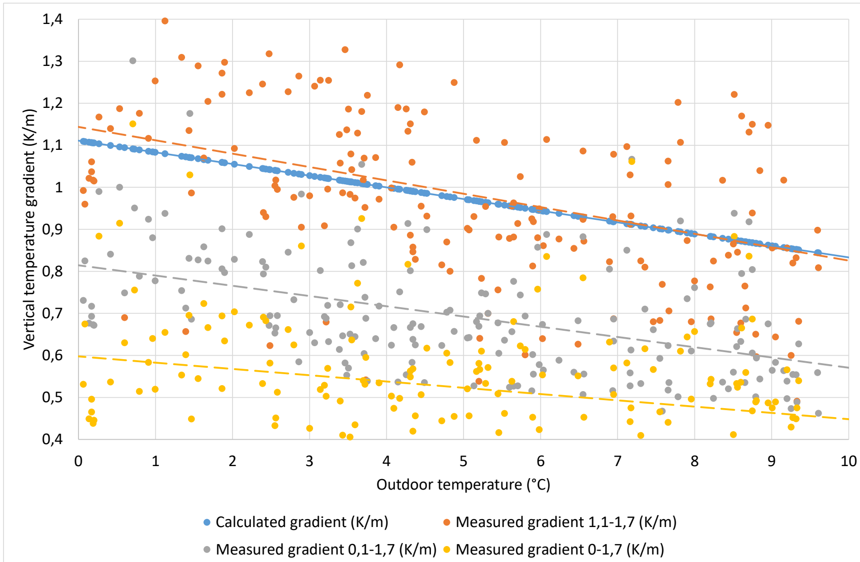

Fig. 4. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 8. 2017-03-12—2017-03-20.

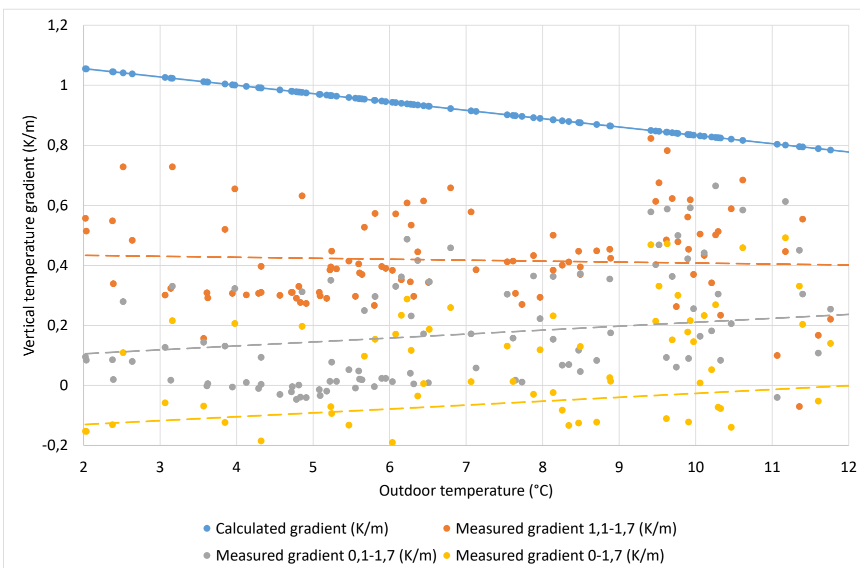

Fig. 5. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 9. 2017-03-23—2017-03-28.

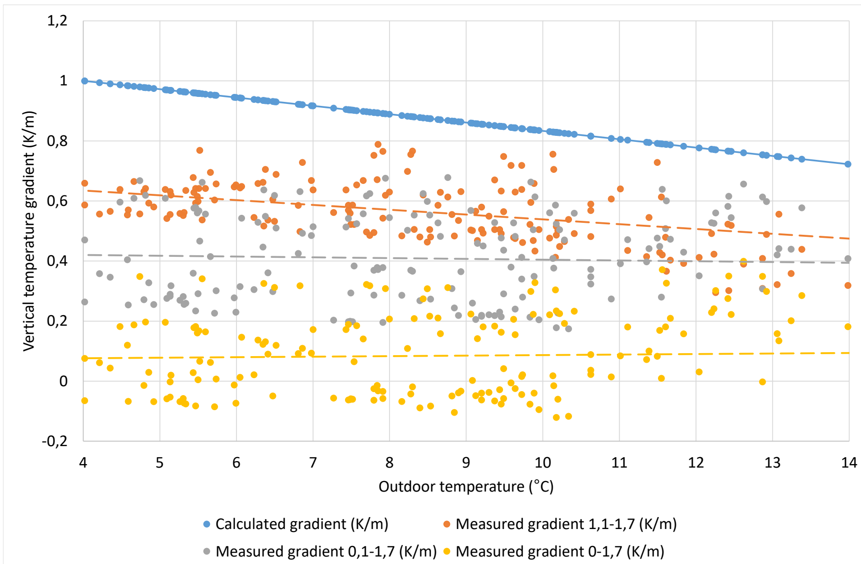

Fig. 6. Vertical temperature gradient as a function of outdoor temperature. Apartment no. 10. 2017-03-28—2017-04-05.

As the gradients not can be expected to be a linear function of the height there could be a difference depending on which heights are used. Compared to the temperature gradient calculated with the proposed equation the measured gradients are generally lower. The largest measured gradient is C, i.e. between 1.1 and 1.7 m above floor. Note that the registered temperature in all cases are somewhat higher on level 0.0 m (floor level) than on 0.1 m, which means that gradient A is the lowest and in apartment 6, 9 and 10 even negative. Some of the gradients are relatively small, 0.2-0.4 K/m, i.e. in the same order of magnitude as the accuracy of the sensors.

Table 3 presents the results from linear regression for the three temperature gradients. To agree with the equation used for recalculation, k should be -0.0278 m^{-1} and l should be 1.11 K/m. Best agreement can be seen for the measured gradient based on temperature difference between 1.1 and 1.7 m above floor. These heights are also those best corresponding to the heights used in the proposed equation (1.2 and 2.1 m). For apartment no. 8 the agreement is very good. Though, the determination coefficient, R^2 is low also in this case. In some cases the slope k is opposite the expected, i.e. the vertical temperature gradient is negative, the higher level the lower temperature. At 0°C outdoor temperature the gradient (l in Table 3) should have been 1.11 K/m, but in nearly all cases it is half or even lower.

Table 3. Results from linear regression.

Apt.	0.0-1.7			0.1-1.7			1.1-1.7		
	k	l	R²	k	l	R²	k	l	R²
3	0.0104	0.2375	0.0117	0.0035	0.4543	0.0019	0.0093	0.3829	0.0226
5	0.0122	0.2535	0.0523	0.0291	0.6082	0.0775	-0.0058	0.6302	0.0049
6	0.0059	-0.1524	0.0054	0.0166	-0.0594	0.0215	0.0103	-0.0600	0.2101
8	-0.0150	0.5977	0.0927	-0.0244	0.8146	0.2915	-0.0318	1.1435	0.1873
9	0.0130	-0.1563	0.0632	0.0131	0.0791	0.0869	-0.0032	0.4396	0.0082
10	0.0017	0.0692	0.0025	-0.0026	0.4307	0.0051	-0.0160	0.6989	0.2882

4 Discussion

The reference height, 1.2 m, used by the company for calculating the apartments' reference temperature in the used system for IMB, is not the same height as used for the measurements in this study. The heights in this study are selected as these are international reference heights, thus making it possible to compare to international and national standards for thermal comfort. But, as a gradient can be calculated based on the difference in heights this should be sufficient.

The temperature measurements have been performed daylong with tenants living as normal as possible, which of course mean lots of disturbances, such as movements, window airing, different presence for different number of persons, lighting and other electrical appliances, etc. and in daytime possibly solar gain through windows. This is of course also the situation in the apartments where the referred IMB-system is used.

Wallentén [9] did measurements in one room in a full scale laboratory with different heat loads and two different placements of the radiator, below the window and at the opposite inner wall, both with and without supply air. During the measurements there was no disturbances from persons nor from window airing. The pattern for the vertical temperature gradient differs a lot, especially can large differences be seen between night and day. For a night case in January 1998, with a radiator heat load of 180 W, it is approximatively 1.4 K/m, both in the inner part of the room and close to the window. The day after, which was sunny, the heat load was zero and the gradient roughly varies from 0.5 K/m close to the inner wall to 1.0 K/m near the window, in both cases without ventilation.

The measurements both in the apartments in this study and in the apartments with the IMB-system were done in the inner parts of the rooms, why it is most relevant to compare them, well aware that even without occupants, the disturbances are large in the whole room volume. The proposed equation emanates from conditions with a linear heat source. The more distributed the heat sources are and the lower their temperature are, the lower will the gradient be. The radiators should have been sized to give accurate power at design heat load with supply temperature 80°C and return temperature 60°C. Very often they, for different reasons, became more or less oversized, which had led to lower maximum temperatures, e.g. between 60 and 70°C was noticed in the referred buildings with IMB-system. This have probably also influenced the gradients measured in this study.

Overall it can be stated that the measured gradients are low, lower than the proposed equation suggests and much lower than the recommended maximum vertical temperature gradient of 3 K/m (SS-EN ISO 7730). The later indicates that the thermal comfort in this aspect for the inner part of the room is good.

The proposed equation seems to over-estimate the vertical gradient. As this recalculation is used when billing heating costs, it is better that the relation is overestimated otherwise the tenants may have had to pay a too high cost.

In this study both day and night temperatures was used. During days disturbances from insolation might have influenced the temperature gradient, even though the sensors were placed in the inner part of the rooms, thus not hit by direct sunlight. Next step could be to separate day and night measurements to see if there are large differences. Anyhow, to be useful, a compromise between conditions during days and nights would be the best choice for the desired purpose, i.e. to recalculate a temperature from a higher to a lower level, more representative to occupants' perception of the operative temperature in a room.

The measurements were done during a limited and fairly mild period and only in ten apartments. The temperature measurements show that the gradients varies both within and between the different apartments. This is reasonable as so many factors influence the indoor temperature, including occupants' behaviours and habits, e.g. opening and closing the windows and vents. Though the varied result, they indicate that the proposed equation for recalculation from 2.1 to 1.2 m above floor overestimate the gradient. To be able to revise the equation, more extended measurements, also comprising periods with outdoor temperatures below zero, preferable down to minus 10°C or lower, should be performed.

5 Conclusions

The gradients recalculated with the proposed equation is in general larger than the measured gradients in the apartments, implying that it overestimates the gradients for the studied conditions.

The measured vertical temperature gradients during the heating season in the inner part of the living room, in apartments heated by a hydronic system and ventilated by mechanical exhaust ventilation, is low.

It can be concluded that the thermal comfort in terms of vertical temperature gradients is sufficient in the studied apartments for the studied conditions.

At least, in the referred system for IMB, the risk that a tenant should be billed for a higher indoor temperature than delivered is minimal.

6 Acknowledgements

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