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Comparing electric heating systems at equal thermal comfort: An experimental investigation

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ABSTRACT

Electric heaters are still widely used for residential heating. It is often believed that electric systems all perform equally; however, this is not the case as diffusors distribute heat in different ways. In this study, an experimental investigation of electric heating systems shows that heat distribution can indeed influence the effectiveness of the equipment to maintain thermal comfort. A baseboard heater, a convector and a radiant heater are compared at equal thermal comfort conditions in a bi-climatic chamber at different cold room temperatures. To demonstrate the repeatability of the results, a statistical analysis is presented. Results show that the convector consumes less energy than the baseboard and radiant heaters despite achieving similar thermal comfort. Though only small differences were observed, the investigation shows that electric heating systems are not all equal in energy efficiency. There is thus an opportunity to improve the heating effectiveness by improving the heat distribution of the equipment.

1. Introduction

The Canadian electricity supply is in most part provided by hydroelectricity [1], a low cost clean energy. This is particularly true in the province of Québec where over 98% of the electricity is produced by hydro-electric dams [1]. In this sense, electric heating is an attractive low cost method for residential heating for areas having ample supply of electricity that produces low greenhouse gas emissions such as in Québec. On the other hand, one could argue that producing heat with a thermal resistance may not be the most sustainable way to maintain thermal comfort from an energy quality point of view [2]. Electricity is a high exergy energy type, as such, converting the electricity to heat, a low exergy energy, could be interpreted as a poor use given the existence of a heat pumps and other ways to heat buildings.

It is well known that electric heaters convert 100% of their power into heat. This has generally been interpreted in the engineering community that electric heating systems all have the same efficiency. Although it is true that they all convert power to heat as efficiently, they do not distribute the generated heat in the same way. Therefore, gains in effectiveness of electric heaters depend on how the heat diffusor will distribute heat inside the room to maintain thermal comfort.

It must also be noted that the primary objective of a residential heating system is not to achieve a setpoint temperature, but rather to achieve thermal comfort. Heating systems should then be compared at equal thermal comfort and not at equal temperature.

Thermal comfort is defined by ASHRAE [3] as: “the condition of mind in which satisfaction is expressed with the thermal environment”. A key feature that arises from this definition is that thermal comfort is a function of both the surrounding environment and the person. As such, to measure thermal comfort, thermal comfort scales such as the predicted mean vote (PMV) have been devised [4]. The *PMV* index has been modeled by Fanger using the heat transfer between the occupant and his environment [4]. This approach to thermal comfort is generally referred to as the rational approach. Basically, at least six governing parameters are included to influence thermal comfort in *PMV*. The four environmental parameters are air temperature, mean radiant temperature, relative humidity and air velocity while the two personal are metabolic heat rate and clothing insulation. As such, a system might provide a lower air temperature and higher radiant temperature while still achieving thermal comfort. This is the case of radiant heating systems that heat the surface.

Other thermal comfort models have also been used such as the standard effective temperature [5] or the more complex human thermal comfort models proposed by Fiala et al. [6]. The latter being more

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useful for detailed analysis of thermal comfort and are generally not used to measure thermal comfort in the built environment.

A second approach to model thermal comfort is the adaptive approach. In this approach, one tries to predict how the occupant adapts to the thermal environment. This adaptation might be behavioural, physiological or even psychological [7]. Adaptive models have in some cases predicted thermal comfort better than PMV [8]; however most of these cases are in naturally ventilated buildings for warm climates where people can act and make changes to their environment (for example open or close a window). Fanger's model [4] is still able to predict thermal comfort well in HVAC controlled buildings. In fact, a recent review of Fanger's research career [9], shows the different experiments that were performed to ensure the accuracy of PMV. Fanger did propose a modification to his model by including the expectancy factor [10]. A factor that takes into account the thermal expectations of an occupant. The weighting factor was added to PMV who still predominantly predicted thermal comfort. It was chosen to measure thermal comfort in this work so as to be comparable with most heating and cooling studies [11,12]. The case of a tightly controlled indoor temperature is also more common for Canadian residences.

Karmann et al. [13] found that there is suggestive evidence that radiant systems provide equal or better thermal comfort when compared to all-air systems. Comparing radiant heating to convective heating, Lin et al. [14] concluded that there is no significant thermal comfort difference between radiant and convective heating devices. Convective heaters provided higher temperature stratification when compared to floor heaters, but this was not significant enough to change the thermal comfort vote.

To reduce air temperature stratification, it was shown that heating from the floor and cooling from the ceiling were best [15]. Olesen also confirmed that floor heating results in better temperature distribution [16]. On the other hand, cooling from the floor and heating from the ceiling provide greater temperature stratification which can be a source of discomfort [3,17,18]. Heat rises, it is then an expected result that heating the lower parts of the room will provide less temperature stratification.

Other source of discomfort is a cold draft from the window. Sevilgen and Kilic [19] mentioned that heating below the windows would counteract uncomfortable cold drafts.

While achieving thermal comfort, there is ample evidence in literature showing that heat distribution can be used to reduce energy consumption in indoor heating.

In a study conducted to achieve energy efficiency by changing the position of a stove for space heating [20], the radiant temperature profile was changed and thermal comfort was achieved while consuming 14% less energy. Simulating a radiant heating system at different locations, with different surface areas and corresponding temperatures, Tye-Gingras and Gosselin [21] showed that all three parameters could affect energy consumption and thermal comfort. Results were presented in pareto front showcasing the trade-off between thermal comfort and energy consumption. Not surprisingly, results showed that a colder room with low thermal comfort consumed less energy.

In a study by Petráš, and Kalús [22], gas radiant heaters where shown to outperform convectors in terms of energy efficiency. Myhren and Holmberg [23] also stated that radiant heating and cooling could potentially save energy. Comparing heating methods. Wang et al. [24] showed through a four node model that thermal comfort could be achieved by floor heating with 10% less energy consumption when compared to convection heaters.

Local heating and cooling techniques have also been investigated. Han et al. [25] showed that radiant heating could save energy in the case of high ceilings. In an office space, Ahmed [26] showed that a local heating system could provide thermal comfort with up to 30% less energy consumption. In this system, hot air from under the office desk provided comfort. The savings are a result of heating a smaller volume situated close to the occupant.

Olesen et al. [27] showed, with bi-climatic chamber experiments, that by increasing the window convection factor, convectors were less efficient as they increased heat loss through the windows. In the same study, they showed that floor heating was most efficient. Sevilgen and Kilic [19] also showed that heating the windows consumes more energy. In a study performed by Inard et al. [28], it was also found that floor and ceiling heating was more energy efficient than the radiator and convector.

It is clear that heat distribution has an influence on both thermal comfort and energy consumption. Convectors have been found to be less efficient since they heat the windows above the installed unit [27,28].

New design of convectors has allowed these systems to better manage the outlet thermal plume. In this study, a convector will be tested against other heating systems. The experimental investigation will compare a convector, a baseboard heater and a radiant heater at equal thermal comfort. All tested equipments are rated at 1000W of electrical power and are installed below the same set of windows. A thermostat using $PMV = 0$ as a setpoint, instead of a prescribed temperature, is used to control the heating systems. The four environmental parameter in Fanger's equation are measured and used in the control system to calculate PMV.

In the first part of this work, the bi-climatic chamber and measurement instrumentation used in the experiments will be described. The experimental procedure will then be explained. This will be followed by a statistical analysis of the experiment to show its consistency and its error intervals. The results of the experiments are then presented and discussed.

2. Experimental apparatus

The experimental measurements are performed using a bi-climatic chamber [29]. Bi-climatic is employed here as opposed to climatic chamber because the chamber has two distinct controlled temperature zones: a cold one and a warm one where the test room resides. Fig. 1a show a plane view of the chamber with a specific reference to the heater and window locations. Fig. 1a illustrates that the cold room is adjacent to the test room's top and left of sides, while the warm room spans the other two borders of this test room. Fig. 1b shows an elevation view of this bi-climatic chamber. The crawl space beneath the test room is also heated like the warm room.

The test room dimensions are 3.66 m (wall1) × 4.88 m (wall2) × 2.44 m (height). Wall 1 and 2 exposed to the cold room are insulated at R20 while walls 3 and 4 have no inside insulation. The ceiling is insulated at R40 and the floor is insulated at R30. Four double glazed windows, two on each wall exposed to the cold room are installed. An interior door gives access to the test room via the warm room. It remained closed during the experiment. These specifications were observed to allow the bi-climatic chamber to respect the CSA-813-13 [30], a standard for thermostat performance. The interest in this bi-climatic chamber also lies in the fact that all interior walls can be modified to simulate different wall types and geometries [29].

In the test room of the chamber, one 1000 W rated electric heating system is installed below the windows of the short wall (wall 1). A total of 53 thermocouple temperature measurements (type K), two power measurements and one thermal comfort measurement are made.

The heating system is controlled via a thermal comfort controller using the thermal comfort measurement as input to the controller and setting the set point of the controller to $PMV = 0$. The thermal comfort is measured at the geometric center of the room. The thermal comfort measurement involves one operative temperature measurement, one air temperature measurement, one humidity measurement and one omnidirectional air velocity measurement. Clothing insulation and metabolic rate are set in the software. The thermal comfort measurement system used is the Dantec Dynamics ComfortSense thermal comfort