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Design considerations with ventilation-radiators: Comparisons to traditional two-panel radiators

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ABSTRACT

Performance of heat emitters in a room is affected by their interaction with the ventilation system. A radiator gives more heat output with increased air flow along its heat transferring surface, and with increased thermal difference to surrounding air. Radiator heat output and comfort temperatures in a small one-person office were studied using different positions for the ventilation air inlet. In two of the four test cases the air inlet was placed between radiator panels to form ventilation-radiator systems. Investigations were made by CFD (Computational Fluid Dynamics) simulations, and included visualisation of thermal comfort conditions, as well as radiator heat output comparisons. The room model was exhaust-ventilated, with an air exchange rate equal to what is recommended for Swedish offices ($7\,\mathrm{l\,s^{-1}}$ per person) and cold infiltration air ($-5\,^\circ\mathrm{C}$) typical of a winter day in Stockholm.

Results showed that under these conditions ventilation-radiators were able to create a more stable thermal climate than the traditional radiator ventilation arrangements. In addition, when using ventilation-radiators the desired thermal climate could be achieved with a radiator surface temperature as much as 7.8 °C lower. It was concluded that in exhaust-ventilated office rooms, ventilation-radiators can provide energy and environmental savings.

1. Introduction

Rising energy prices and a wish to create environmental friendly HVAC systems increase the demand for thermally efficient heating systems. Increasing efficiency of radiators allows for a lower water temperature in the radiator circuits. This may result in several positive environmental and economic aspects, such as:

- More efficient energy production by heat pumps, sun panels or similar.
- Reduced heat losses in the distribution net of district heating systems, and facilitation of alternative heating and waste heat retrieval [1].
- Improved thermal climate for occupants. Indoor thermal climate with low temperature systems is assumed better for human health than that provided by high temperature heating systems. Studies show that low temperature heating systems create more stable and uniform indoor climate, with lower air speeds and lower temperature differences [2,3].

Heat output from radiators and vertical plates with natural or forced convection have been calculated analytically and investigated by CFD simulations in several studies [4–6] at the Royal Institute of Technology, School of Technology and Health (KTH-STH) in Stockholm. The main goal has been to find ways to increase the thermal efficiency of radiators. It was found that that enlarging or modifying existing radiators or adding convection fins may increase thermal efficiency. The drawback of such changes, however, has often been increased production costs. Attention therefore turned to ways of boosting heat output that might be easier and less costly, such as directing ventilation air towards heated radiator surfaces, or forcing air between radiator panels.

This paper reports on four test cases investigating how much thermal efficiency may be improved and how thermal comfort in the room can be affected by simply changing the position of the ventilation air inlet in relation to the radiator. Cases A and B used traditional radiators and different positions of the air inlet. Cases C and D used innovative ventilation-radiators with different widths between the radiator panels. All investigations were done by CFD simulations in an exhaust ventilated office model exposed to Swedish winter conditions.

The purpose of the study was to provide guidance for manufacturers of heating and ventilation systems. A secondary

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Nomenclature

A	heat transferring surface area of radiator (m^2)
c_p	specific heat capacity ($\mathrm{W\,s\,kg^{-1}\,{}^\circ C^{-1}}$)
COP	coefficient of performance of heat pump
$\mathrm{COP_C}$	theoretical coefficient of performance of heat pump
d_h	hydraulic diameter (m)
g	gravity ($\mathrm{m\,s^{-2}}$)
Gr	Grashof number
h	height (m)
k	total heat transfer coefficient ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
L	characteristic length (m)
L_per	wetted perimeter (m)
$\dot{m}$	mass flow ($\mathrm{kg\,s^{-1}}$)
Nu	Nusselt number
Nu_dh	Nusselt number in duct
P	heat output (W)
Pr	Prandtl number
$\dot{Q}$	total heating power (W)
Ra	Rayleigh number
Re	Reynolds number
Re_dh	Reynolds number in duct
T_1	evaporator temperature (K)
T_2	condenser temperature (K)
u	air speed ($\mathrm{m\,s^{-1}}$)
U	heat transfer coefficient through building envelope ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
$\dot{W}$	compressor power (W)

Greek symbols

$\Delta\theta$	temperature difference between water entering and leaving the radiator (°C)
$\Delta\theta_\mathrm{CFD}$	temperature difference between radiator and ambient air in CFD sim. (°C)
$\Delta\theta_\mathrm{m}$	mean temperature difference between heated surface and ambient air (°C)
α_conv	convection heat transfer coefficient at radiator surface ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
α_ins	heat transfer coefficient between internal water and radiator ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
α_out	heat transfer coefficient between radiator and air ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
α_rad	radiative heat transfer coefficient at radiator surface ($\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$)
β	coefficient of expansion ($\mathrm{{}^\circ C^{-1}}$)
δ	radiator wall thickness (m)
η_Ct	Carnot efficiency
λ	conductivity ($\mathrm{W\,m^{-1}\,{}^\circ C^{-1}}$)
θ_air	mean room air temperature (°C)
θ_comfort	comfort temperature (°C)
θ_sur	radiator surface temperature (°C)
$\theta_\mathrm{water,in}$	water inlet temperature (°C)
$\theta_\mathrm{water,out}$	water outlet temperature (°C)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)

objective was to demonstrate how CFD simulations may be used to illustrate indoor climate in a nuanced way.

Results were evaluated with reference to recommendations in ISO 7730:1994, an international standard that specifies conditions for thermal comfort [7].

2. Theory

2.1. Heat transfer of a radiator

The correlation in a heat transfer process from warm water inside a radiator to air and room surfaces surrounding the radiator is illustrated in Fig. 1, and summarised in Eq. (1) below.

$$\dot{m}\cdot c_\mathrm{p}\cdot\Delta\theta = k\cdot A\cdot\Delta\theta_\mathrm{m} \tag{1}$$

Here the parameters on the left side, $\dot{m}$, c_p and $\Delta\theta$, are the mass flow of water inside the radiator, specific heat capacity of water and temperature difference of water entering and leaving the radiator ($\theta_\mathrm{water,in} - \theta_\mathrm{water,out} = \Delta\theta$).

The parameters on the right side are the total heat transfer coefficient, k, area of the radiator surface, A, and the mean temperature difference between radiator surface and ambient air, $\Delta\theta_\mathrm{m}$.

The expression of $\Delta\theta_\mathrm{m}$ is given below.

$$\Delta\theta_\mathrm{m} = \frac{\theta_\mathrm{water,in} - \theta_\mathrm{water,out}}{\ln(\theta_\mathrm{water,in} - \theta_\mathrm{air}/\theta_\mathrm{water,out} - \theta_\mathrm{air})} \tag{2}$$

where θ_air is the mean room air temperature.

The total heat transfer coefficient, k, is given by.

$$\frac{1}{k} = \frac{1}{\alpha_\mathrm{ins}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_\mathrm{out}} \tag{3}$$

where the terms on the right hand side represent the heat transfer from water to surface inside the radiator, conduction heat transfer though the radiator wall and heat transfer from the radiator surface to ambient air on the outside wall, respectively. The thickness of the radiator wall is given by δ and conductivity by λ. The limiting factor in the heat transfer, α_out, contains both a radiative and a convective part, α_rad and α_conv. Eq. (4) describes the configuration of α_conv.

$$\alpha_\mathrm{conv} = Nu\cdot\frac{\lambda}{h} \tag{4}$$

where λ is the conductivity of air (set to 0.025 $\mathrm{W\,m^{-1}\,{}^\circ C^{-1}}$ in this study) and h is the height of the heated vertical surface. The dimensionless Nusselt number, Nu, is in a natural convection situation on a single vertical surface based on the Rayleigh number,

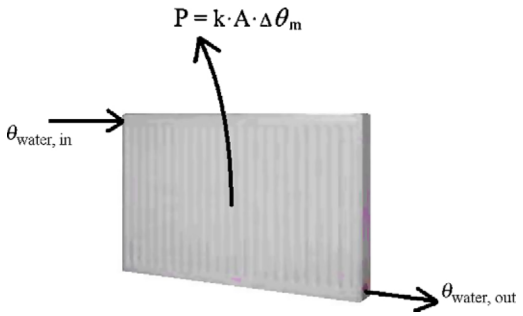

Fig. 1. Heat transfer process of a radiator. The amount of heat emitted from a radiator, P, is the product of the parameters on the right hand side of Eq. (1). P is also equal to the heating power provided by warm water passing through the radiator, shown as the product of the parameters on the left hand side of Eq. (1).