A Novel Personal Comfort System: A Radiant Desk With a Loop Heat Pipe

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Abstract

This study is the second step toward the development and prototyping of a Personal Comfort System for tertiary sector working environments. The entire industrial sector, and, in particular, offices, have seen changes in working habits, with a large increase in smart working also due to prevention of COVID infection. The chance to partialize the HVAC system and maintain rooms in an under-conditioned state is the obligatory way towards reducing energy waste, providing each workstation with an independent system that guarantees the operator's comfort conditions. The goal of the second step presented in this work was to size and optimize the radiating desk, with the aim of testing an experimental demonstrator. A LHP was chosen to bring heat from the source to the desk, decoupling the heat generation and heat distribution system, without the need for additional parasitic power consumption or moving parts, adding to the innovation of the proposed design. The ergonomic optimization of the surface and its power reduction did not affect its ability to improve localized comfort, since the operators' conditions move from a slightly cold to a neutral situation. Moreover, no discomfort due to vertical temperature differences or radiant asymmetries were found. Therefore, the next research step will lead to prototype creation and its analyses, conducted in a climatic room to test if the distribution system can satisfy comfort thermal requirements with probes as well as real users.

1. Introduction

Reducing energy consumption is a current issue, made increasingly stringent with the progress of the 21st century (Allouhi et al., 2015; Almasri & Alshitawi, 2022). The total energy consumption associated with HVAC services (heating, ventilation, and air conditioning) in buildings accounts for 40 % of total energy consumption in Europe and 36 % of greenhouse gas emissions (EU. Buildings, 2020).

New methods of building design and HVAC systems are becoming increasingly popular, yet people still often complain of thermal discomfort (Fantozzi et al., 2020; Ortiz et al., 2017), and inadequate attention is paid to reducing energy waste (Carmenate et al., 2016; Li et al., 2019). Moreover, buildings do not meet the regulations' modest goal of having no more than 20 % unsatisfied occupants, primarily due to building over-conditioning and occupants' inability to adjust the environment individually to meet their personal needs (Brager et al., 2015).

The importance of providing Indoor Environmental Quality (IEQ) is widely recognised (Lamberti, 2020), especially in the work-place, where not only personal well-being increases productivity (Greenberger et al., 1989; Rocca et al., 2020), but it also makes up the greatest component towards dissatisfaction (Frontczak et al., 2012; Huizenga et al., 2006). The IEQ is defined by many interacting factors (Bluyssen, 2020), among which thermal comfort is the most significant on the perception of environmental quality and the energy consumption associated with IEQ achievement (Lamberti, 2020). As the individual differences based on age, gender, or body fat content show, thermal comfort is not only a simple function of the thermal environment, but it is also influenced by a whole set of individual factors. Thermal neutrality is considered to provide the best comfort, but this does not respect individual preferences (Fantozzi et al., 2021; van Hoof, 2008).

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Personal ability to thermoregulate oneself plays a key role in this process (de Dear et al., 2013). Therefore, the local microenvironment needs to become personalized to fit the preferences of everyone.

Individually oriented new approaches are under development in this emerging research area, to evaluate the average zone thermal comfort metrics. For instance, a personal comfort model predicts individuals' thermal comfort responses, instead of the average response of a large population with an improved comfort predictive power compared to conventional models (PMV, Adaptive) (Kim et al., 2018).

A noteworthy model is the Berkeley Comfort Model, which predicts the sensation for each local body part with input data related to skin temperature (Huizenga et al., 2001); a physical measurement campaign or a thermophysiological computer program that treats the body as multiple segments would be needed to simulate this data (Zhang et al., 2010a; Zhang et al., 2010b). Thermal sensation and comfort for local body parts vary greatly and affect thermal sensation and comfort perceived for the whole body (Arens et al., 2006a). In a cool environment, hands and feet feel colder than other body parts, and feet are the major sources of discomfort (Arens et al., 2006b; Zhang et al., 2010c). In the tests performed by Arens et al, people perceived neutral conditions as "comfortable", but the "very comfortable" rating was achieved only in the asymmetric or transient environment conditions, which can be achieved through local Personal Comfort Systems (PCS), defined as systems that heat and cool individuals without affecting the environments of surrounding occupants (Arens et al., 2006a).

PCSs play an important role in this landscape with the target of conditioning only the "personal" microclimate rather than the volume of the entire building, in contrast to traditional HVAC systems (Kalaimani et al., 2020).

PCSs provide a series of benefits to indoor environments, like ensuring comfort conditions (Tsuzuki et al., 1999; Warthmann et al., 2018; Zhang et al., 2010) and reducing energy waste (Godithi et al., 2019; Shahzad et al., 2018; Zhang et al., 2015). They can provide comfort conditions with an environment temperature as low as 15 °C (Veselý & Zeiler, 2014). Zhang et al. found that there are several benefits to providing personal control over an environmental feature capable of providing a local pleasurable sensation (Zhang et al., 2010c).

The present study is the second step of a research study aimed at prototyping a radiant-conductive system to guarantee microclimatic comfort conditions in open-space offices, transferring heat directly to the person (Rugani et al., 2021). Furthermore, reducing air movement will bring about the additional benefit of reducing the movement of pollutants and micro-particulates.

The global COVID-19 pandemic has increased cases of smart-working, often causing office staff presence to be significantly lowered. The direct consequence was seen in the wasted energy needed to air-condition entire offices where most desks remained empty (Jiang et al., 2021). PCSs can provide microclimatic comfort for operators, and the possibility of reducing the setpoint temperatures of the primary HVAC system would lead to a drastic reduction in energy losses (Rugani et al., 2021). The trend is generally to rethink design strategies as a result of the pandemic (Megahed & Ghoneim, 2021), rethinking buildings both from a spatial point of view, but also in terms of HVAC systems.

Therefore, the prototypisation of a bespoke radiant surface embedded in a desk and the study of the comfort conditions that this can provide is the objective of the research. In this second research step, the preparatory analyses were carried out considering a Loop Heat Pipe (LHP) as the thermal vector from the heat source and the radiant plate. LHPs are a passive devices, whose heat transfer and fluid motions are ensured by cycles of evaporation and condensation of a working fluid. Hence the lack of need for pumps or additional energy sources for their operation makes up their great scientific interest.

2. Method

2.1 Overview

The aim of the study is to prototype and optimise a Personal Comfort System (PCS). In the previous phase, the PCS was conceived and studied as a complete radiant desk, analysing the comfort provided to the user according to the potential energy savings in offices (Rugani et al., 2021).

Two possibilities were identified for transferring heat to the desk - via a hydronic system and via an electric infrared surface. The objective of the current research is the sizing of the hydronic one, with the application of a Loop Heat Pipe. It allows the parasitic energy consumption of the pump for a standard hydronic system to be saved and a plug-in desk, versatile and easily interfaced with the energy sources, with no moving parts and no risk of failure to be created.

The analysis consisted of a first phase of the LHP condenser sizing, i.e., the radiant plate to be placed in the desk, simulating it in the operating conditions. Several condensers designed were studied to find the most efficient one. Meanwhile, CFD analysis with a similar methodology to the previous study by the Authors was conducted, simulated in two different heating system configurations: heating with standard setpoint and underconditioned state with local PCS.

2.2 LHP Design

LHPs have been widely implemented in space applications and thermal management, for which they were first created in the early 70s. They are a two-phase passive heat exchanger, able to transfer heat over several meters without the need for moving parts or any additional energy for its functioning. This would reduce power consumption and the noise in using a hydraulic active system, the complexity, and the risk of failure, hence increasing the overall system efficiency. LHPs work thanks to the cyclic evaporation/condensation processes of a working fluid, whose motion is ensured by a positive pressure gradient arising in a porous structure, due to capillarity (Maydanik, 2005). LHPs have been extensively studied in recent years in several applications, like aircraft (Pagnoni et al., 2021) and electric vehicle thermal management (Bernagozzi et al., 2021), solar water heating (Wang & Yang, 2014), and electronics cooling (Domiciano et al., 2022).

The LHP has the function of transferring heat from the source (evaporator) to the radiating desk (condenser). Its sizing was performed thanks to a validated Lumped Parameter Model (LPM) code validated by Bernagozzi et al. (2018). The power of the system was chosen according to the previous analysis performed. Compared with the first study, the power range was reduced because the radiating surface was optimized, according to an ergonomic study about the user's position. Values aligned with those previously identified by Mao et al. (2017), who provided the desk with a palm warmer with a power consumption of 26 W at steady state (typical surface temperature of 35 °C).

Fig. 1 shows the condenser, which represents the heating plate, located in the desk. Fig. 2 shows the desk section with the embedded condenser of the LHP. This will be a small diameter meandering pipe where condensation of the working fluid takes place, ensuring a constant temperature profile along the radiating surface, ultimately increasing the individual's feeling of comfort.

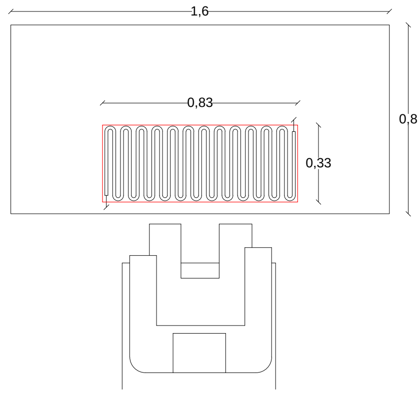

Fig. 1 – Example of a desk configuration, with the heating plate facing the user

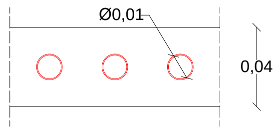

Fig. 2 – Desk section

2.3 CFD Modeling

A CFD analysis was conducted using Autocad CFD software. The purpose was to obtain the local environmental conditions on an ideal manikin placed on a chair in front of the desk. Solving the Navier-Stokes equations allowed an assessment of the local comfort conditions and the convective and radiant energy contributions of the PCS, which are impossible to evaluate with a Building Energy Simulation (BES).

CFD models have been widely adopted as effective tool for natural ventilation simulations, while BES is more stable with the heat transfer between solid and fluid (Zhang et al., 2013). Moreover, the effect of air mixing considerably affects the zone temperatures. Thus, CFD analysis is the most suitable option for assessing the temperature variation (Jones et al., 2020; Salimi & Hammad, 2020).

Following the previous methodology, two configurations were studied: heating with standard set-point (21 °C), and PCS in an under-conditioned environment (17 °C).

The CFD simulations aimed at evaluating the size and shape of the condenser in ensuring user comfort. Thus, this phase was conducted in parallel with the calculation of the LHP system.

2.4 Comfort Assessments

To determine thermal comfort, several models were developed. Most of the research conducted on the assessment of comfort conditions were based on Fanger's thermal model and the calculation of the two indices: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) (ISO 7730:2005 2005).

Individual-oriented models, such as the Berkeley Comfort Model, while more effective at predicting local response, require experimental data on a physical person. Although Fanger's indexes were created for the evaluation of general comfort, several studies demonstrated its ability to compare thermal comfort from different setups (Orosa Jose, 2010; Shahzad et al., 2018; Zhang et al., 2015).

To compare the case study results to the previous analysis (Rugani et al., 2021) and to the research conducted by Shahzad et al. (2018), the applied conditions are those shown in Table 1.

Table 1 – Comfort evaluation parameters for Fanger's model

Humidity (RH)	30%
Metabolic rate (MET)	1
Clothing insulation (CLO)	0.7

Furthermore, two local models based on environmental data were applied (ASHRAE, 2021): discomfort due to vertical temperature difference (1), and discomfort due to radiant asymmetry (2-3). Also, specific standards on heating radiant systems such as EN ISO 11855 (ISO, 2021) indicate following the previous models for local discomfort evaluation.

$$PD = 100/1 + \exp\,(5.76 - 0.856 \cdot \Delta t_{a,v}) \qquad (1)$$

$$PD = 100/1 + \exp\,(6.61 - 0.345 \cdot \Delta t_{pr}) \qquad (2)$$

$$PD = 100/1 + \exp\,(9.93 - 0.50 \cdot \Delta t_{pr}) \qquad (3)$$

Where PD is the Percentage Dissatisfied and Δt are the temperature differences in each case.

The limits prescribed by the regulations are applied, with particular attention to temperature differences. The vertical temperature gradient between head and feet is prescribed as 3 °C/m by ASHRAE 55 (ASHRAE 2020) and ISO 7730 (ISO 7730:2005 2005). Nevertheless, Liu et al. (2020) found that vertical temperature gradient changes with thermal sensation votes and could be increased to 5 °C/m when the subject is thermally neutral.

3. Results

Different heating inputs were provided to the LHP evaporator to achieve the optimum desk surface temperature of 36 °C, namely 15 W, 20 W, 25 W, and 30 W. Moreover, several working fluids were investigated for the LHP: water, acetone, ethanol, R1233, and Novec649. Finally, tubes of various sizes were tested, with internal radius of 4, 5, and 6 mm.

Figs. 3, 4, and 5 show the superficial temperature variation of the desk as a function of the working fluid, the heating power, and the pipes dimension.

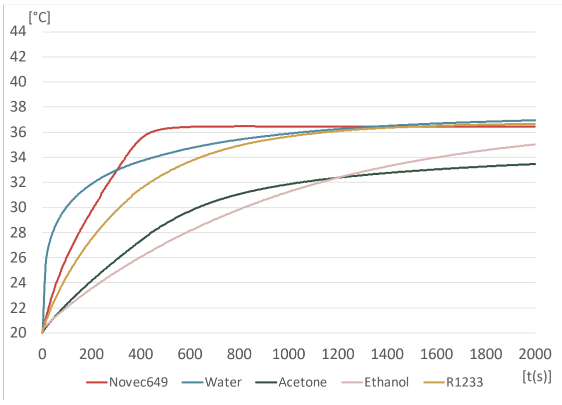

Fig. 3 – Radiant surface temperature of the desk as a function of the liquid in the LHP loop, with a power of 20W and an internal radius of 6 mm

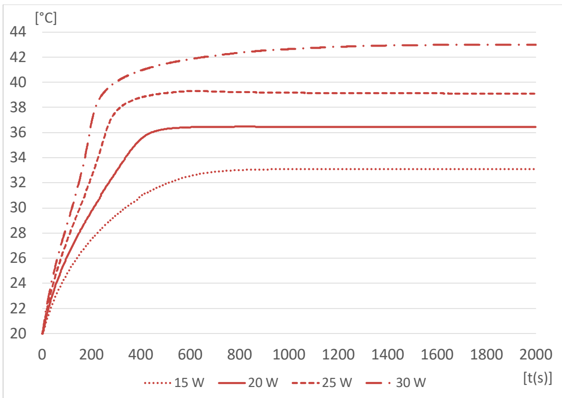

Fig. 4 – Radiant surface temperature of the desk as a function of the power applied to the evaporator, Novec649 in the loop and an internal radius of 6 mm

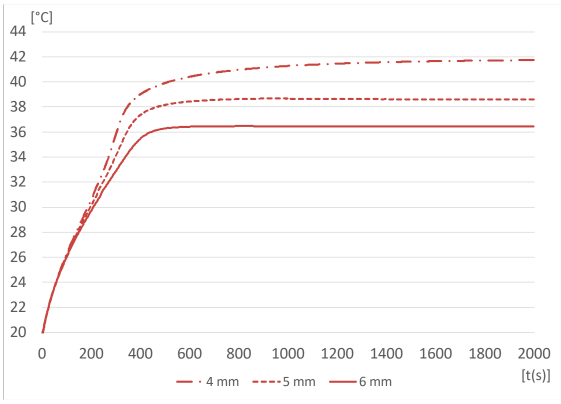

Fig. 5 – Radiant surface temperature of the desk as a function of the pipes dimension, Novec649 in the loop and a power of 20W

The CFD results allowed the overall comfort situation (Fig. 6) and the temperature distributions around the workers to be studied (Fig. 7).

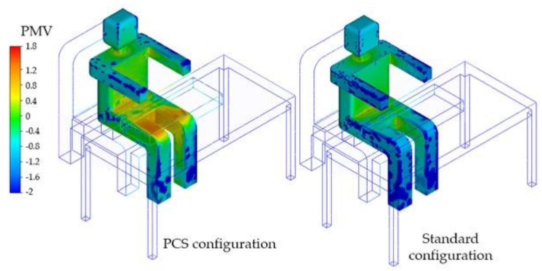

Fig. 6 – PMV distribution at each point of the environment

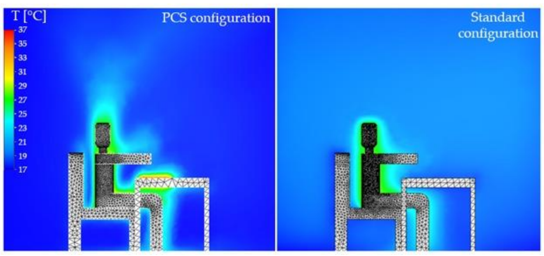

Fig. 7 – Temperature distribution at each point of the environment

4. Discussion

The coupling of CFD and LHP sizing calculations allowed optimization of the heating plate, i.e., the LHP condenser, with the aim of creating a real prototype.

Sizing results showed that the most efficient working fluid was the heat transfer fluid Novec™ 649, produced by 3M™, as it condensed earlier than other liquids and allowed the system to be operative in the shortest time. Interestingly, in the design configuration, 20 W was the power that allows the desired desk surface temperature to be reached, associated with pipes whose inner radius was 6 mm. This low value of power opens up different avenues on heat recovery, for instance, suggesting the use of the waste heat from the electronic components present on the desk, e.g., laptop.

The CFD results show an alignment with those of the first step of the research (Rugani et al., 2021). Although the heating surface area was reduced to 0.27 m^2, as well as the power delivered, the general comfort situation was not affected. The ergonomic study prior to prototyping thus succeeded in optimizing the panel while maintaining its ability to ensure local comfort (Table 2).

Table 2 – Localized results of CFD analyses

	PCS		Standard	
	PMV	*PPD*	*PMV*	*PPD*
Face	-0.06	5	-0.27	7
Torso	0.11	5	-0.42	9
Knee	0.23	6	-0.47	10

A further step conducted in this analysis phase was to verify the compliance of local discomfort models for vertical air temperature difference and radiant asymmetry. There are no major temperature differences between the ankles and the head, as the surface heats in both directions. The PD value is below 1. Likewise, vertical radiant asymmetry discomfort from cold ceilings hardly exceeds PD value 1. On the other hand, if the radiating desk were located near a cold wall, the discomfort from radiant asymmetry could lead to a PD value of 2 with a temperature difference of 8 °C, which in any case is lower than the 10 °C indicated as the standard limit.

5. Conclusion

Today's society demands quality and comfort, especially in the workplace. This study aims to increase comfort and satisfaction with the thermal microclimate in large offices.

The global pandemic has accentuated smart working. Thus, the possibility of being able to partialize thermal systems and to locally heat and cool only occupied workstations is a winning strategy for reducing energy waste.

A first step of this research was conducted to analyze the thermal comfort provided by a radiant desk combined with the associated energy savings. The goal of the second step presented in this work was to size and optimize the radiating desk, with the aim of testing an experimental demonstrator.

A LHP was chosen to bring heat from the source to the serpentine on the horizontal table. Its sizing was performed thanks to a validated Lumped Parameter Model (LPM). 20 W was the power that allows reaching the desired desk surface temperature, associated with pipes whose inner radius was 6 mm.

The CFD results confirmed the ability of the PCS to ensure comfortable conditions even at sub-comfort room temperatures, moving to a neutral situation with PMV value near to 0 (face -0.06, torso 0.11, knee 0.23), thus reducing energy losses from heating entire rooms, such as open space offices, recently left almost empty due to the increase in smart working.

The ergonomic optimisation of the surface and its power reduction did not affect its ability to improve localised comfort. Moreover, no discomfort due to vertical temperature differences or radiant asymmetries was found, with PD below 1 and temperature gradients not exceeding regulatory limits.

Summarizing, the contribution of this work is twofold: firstly, the improvement of the individual's comfort by the adoption of microclimatic comfort; secondly, the system allows an increase in the efficiency of the building's HVAC system, reducing energy consumption and moving a few steps in the net-zero direction.

Future research developments include the comparison of this hydronic desk with a similar electrically powered desk. The reason for this analysis is to conduct an exergetic comparison by contrasting the quality of energy with the versatility and efficiency of systems to ensure local comfort and reduce energy consumption.

Moreover, analyses will be conducted in a climatic room to test that the distribution system can satisfy comfort thermal requirements with probes, as well as real users. Additionally, The CFD model will be rebuilt and validated with ANSYS Fluent software.

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