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Heat flux measurements from a human forearm under natural convection and isothermal jets

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ABSTRACT

Heat transfer from a human forearm to a large jet, representative of a building HVAC vent/outlet was studied using both an IR camera and a heat flux sensor. The isothermal jet was discharged horizontally from a wind tunnel, at the same temperature as the ambient air. A model cylinder was used to validate the heat transfer results with results from previous studies, using both an IR camera and heat flux sensors. The same jet was used for studies from a human forearm at various Reynolds numbers (Re = 9500–41,000) and impinging distances of four and eight jet diameters The results were compared with heat transfer due to natural convection under both open and controlled environments. A significant increase in convection heat transfer with Reynolds number and distance from the jet outlet was observed. A nearly fourfold increase in convection heat transfer coefficient was obtained when a jet with Reynolds number of 9500 was impinged on a human arm when compared to that obtained under natural convection in an open environment. Empirical correlations for predicting the stagnation and average Nusselt number from a human arm were also developed with high values of correlation coefficients for future studies. Overall, impingement jets were found to be an effective means to transfer heat from human bodies and could potentially be used for creating thermally conditioned microenvironments.

1. Introduction

Microenvironment conditioning refers to controlling the thermal properties of a small zone around the object to be conditioned, based on the thermal behavior of the object [1]. Such a system can be used to cater to the comfort needs of multiple individuals and at the same time, reduce energy consumption needs for air conditioning of building spaces. Microenvironment creation units currently available in the market are either floor mounted or desk mounted [2]. For a working model of a system as proposed in this study, the traditional HVAC vent system was replaced with a nozzle with directional flexibility, so that the jet can be maneuvered to aim the flow of air at a different direction as needed.

Impingement jets have been used in a variety of applications to provide high convective heat transfer rates, including cooling of stock material during material forming processes [3], cooling of electronic components and turbine components, and other industrial processes. A range of uses and performance of impingement jets can be found in a number of reviews [4–6]. Heat transfer from an isothermal impingement jet of air depends on the curvature of the cylinder relative to the jet nozzle diameter, the distance of the cylinder from the jet nozzle relative to the jet nozzle diameter, Reynolds number, turbulence intensity and the geometry of the nozzle [5]. Cornaro et al. [7] studied the heat transfer from a convex surface to isothermal impingement jets over a range of Reynolds number ($Re = 6000–16,000$), jet exit-to-surface spacing ($z/d = 1–4$) and cylinder to jet nozzle diameters ($D/d = 2.63–5.55$). They concluded that the heat transfer increases with Reynolds number and curvature. Lee et al. [8] also considered large cylinders, with similar conclusions.

Very little literature was found for large isothermal jets impinging on small cylinders ($D/d < 1$) and the circumferential variation of Frossling numbers with Reynolds numbers for such cases. Tawfek [9] studied the circumferential and radial distribution of Nusselt number for small cylinders over a range of Reynolds numbers ($Re = 3800–40,000$) and impingement distances ($z/d = 7–30$). It was found that the drop in Nusselt number with increasing radial angle from the impingement points was higher for smaller nozzle to surface distances and smaller jet diameters. An increase in surface curvature was found to increase stagnation Nusselt number values. Wang et al. [10] discussed the heat transfer characteristics of a cylinder in crossflow for a range of curvature ratios ($D/d = 5, 1, 0.5$) at a jet Reynolds number of 20,000. They found that for small cylinders (D/d < 0.5) the heat transfer characteristics was similar to that of a cylinder immersed a uniform

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Nomenclature

A	surface area of the heater (m^2)
D	diameter of the cylinder (m)
d	diameter of the jet nozzle (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
q''	heat flux (W/m^2)
R	resistance (Ω)
S	sensitivity of the heat flux sensor ($V/W/m^2$)
T	temperature (°C)
t	thickness
v	centerline jet velocity (m/s)
V	voltage (V)
z	impinging distance from the jet origin (m)
θ	angle with respect to the impingement point or horizontal (deg.)
ε	emissivity of the surface
σ	Stefan-Boltzmann constant

Non-dimensional numbers

Fr	Frossling number; $\left(\frac{Nu}{\sqrt{Re_D}}\right)$
Nu	local Nusselt number; $\left(\frac{hD}{k}\right)$
Re_D	Reynolds number based on cylinder diameter; $\left(\frac{\rho v_0 D}{\mu}\right)$

Subscripts

0	jet exit properties
Al	aluminum
avg	average
cond	conduction
conv	convection
in	input properties of the heater
inf	ambient fluid properties or enclosure wall properties
r	radial direction
rad	radiation
s	distance along circumference of the cylinder (m)

crossflow and that larger cylinders behaved similar to that of a flat plate. It was also found that inside the potential core region of the jet, where the centerline velocity of the jet is unchanged, the stagnation heat transfer was found to be higher for smaller cylinders whereas outside the potential core, larger cylinders provided higher stagnation heat transfer. Balasubramanium [11] studied the effects of impinging distances for isothermal and non-isothermal jets impinging on small cylinders (D/d < 1). It was found that heat transfer was influenced by impinging distances, temperature and turbulence characteristics of the jet. Stagnation Nusselt number was found to match closely for both isothermal and non-isothermal jets at a fixed Reynolds number. The Frossling number distribution over the front portion of the cylinder ($\theta = 0$–90°), based on the local centerline impinging temperature, was also found to be similar for both isothermal and non-isothermal jets at $z/d = 4, 8$. Variation of Frossling number along the lateral direction was found to be about 5% at a distance of $0.6d$ as compared to that at the impingement point and this variation was found to be lesser at larger impingement distances.

Human thermal comfort is affected by external environmental conditions, clothing and physical activity. According to the definition by ASHRAE, thermal comfort is a subjective response or condition of mind that expresses satisfaction with the surrounding thermal environment [12]. This standard is based on Fanger's "comfort equation", a heat balance model of a human body [13]. This method suggests calculation of a Predicted Mean Vote (PMV) index for identifying the thermal comfort of an environment based on seven different parameters: air temperature, air velocity, mean radiant temperature, humidity, clothing and activity. This index varies between −3 for cold to +3 for hot. Another index named Predicted Percentage Dissatisfied (PPD) measures the degree of discomfort, predicts the percentage of people dissatisfied with the environment conditions, and the index value varies between 5% and 100%. However, these methods do not measure the heat flux directly but instead estimate it empirically, using temperature and other environmental conditions. A heat flux sensor on the other hand can be used to measure the heat flux from different parts of a human body directly. A heat flux sensor can also be integrated into a wearable electronic device to connect with the air-conditioning system, thus, helping personalize air conditioning.

There are several computational and experimental studies done on heat transfer from a human body to external environment under natural convection and convective flow of air over the entire body or a thermal manikin [14–17]. Richard De Dear et al. [18] studied heat transfer from different body segments of a thermal manikin under natural and forced convection. The speed of uniform flow of air for this study ranged from 0 to 5 m/s. A radiative heat transfer coefficient of 4.5 W/m^2 K was obtained. Hands, feet and peripheral limbs were found to have higher convective heat transfer coefficients than the central torso region. Li et al. [19] studied the effects of strong convective flow on the human body. The convective heat transfer coefficient increased as the square root of the wind velocity for velocities from 1.1 to 12.7 m/s. For this range the convective heat transfer varied from 16.7 W/m^2 K to 71 W/m^2 K.

The present study experimentally measures the heat transfer characteristics of a horizontal isothermal jet of diameter, d, impinging on a human arm in such a thermal microenvironment, over a range of Reynolds numbers. A cylinder of diameter 'D', similar to the diameter of a human arm, was used to validate heat transfer results using an IR camera and heat flux sensors with results from previous studies. Experiments on circumferential variation of heat transfer to impingement jets from a human forearm were performed using a heat flux sensor. These results were compared with heat transfer results obtained for natural convection. A sample use case for the Nusselt number-Reynolds number correlation developed in this study is also presented.

2. Experimental setup

A schematic diagram and a photo of the experimental setup is shown in Fig. 1. An isothermal jet of diameter, 'd' was impinged on a uniformly heated cylinder of diameter 'D' at a distance 'z' from the nozzle opening. The impingement jet was generated using an axial fan wind tunnel. The DC powered fan draws in air at room temperature from the surroundings. The speed of the fan is controlled by varying the input voltage to the fan. The inner diameter of the circular wind tunnel is 12.9 cm and is 167.6 cm length. Flow straighteners are placed inside the wind tunnel at a distance of 122 cm from the fan to straighten any rotational component of velocity of air inside the wind tunnel. In addition, fiberglass screen meshes are also placed in the wind tunnel at a distance of 30.5, 81.3 and 168 cm from the fan to break the formation of boundary layers and make the axial velocity uniform. Velocity at the end of the wind tunnel was measured using a pitot tube and manometer (Dwyer Mark II).