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Heat transfer effects of chimney height, diameter, and Prandtl number☆

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ABSTRACT

This study investigates the heat transfer enhancement of a chimney system, both experimentally and numerically, by varying the height and diameter of the chimney, and the Prandtl number of the working fluid. Mass transfer experiments are carried out using a sulfuric acid and copper sulfate electroplating system based on analogy concepts. Numerical simulations are executed using FLUENT 6.3. Natural convection experiments and numerical calculations performed without a chimney showed good agreement with the Le Fevre correlation for natural convection on a vertical plate. As the chimney height is increased, the heat transfer rates are enhanced for all Prandtl numbers, but the enhancement rates decrease as the Prandtl number increases. An optimal chimney diameter is found that maximizes the heat transfer. An increase in heat input or heated length results in an additional enhancement of the heat transfer, increasing the buoyancy force. Numerical results provide visualizations of the temperature and velocity fields in the chimneys, showing their interactions and flow regimes.

1. Introduction

A chimney is an extension of the unheated length of a duct above a heated wall, acting as a shroud for a heated plume. Its height determines the acceleration of the hot plume; thus, heat transfer is enhanced with increasing chimney height since flow rate is increased [1].

Lots of experimental and numerical studies on chimney systems have been reported. Recent research on chimney effects has focused on finding optimal configurations to improve the heat transfer parameters [2]. However, experimental studies are relatively rare due to the high cost of large facilities and the difficulty in controlling experimental conditions. Most studies of chimney systems are performed numerically, varying parameters such as the cross-section and height of a chimney [3–9].

This study experimentally and numerically investigates the heat transfer enhancement of a chimney system by varying the height for a range of Prandtl numbers. Experiments were performed using vertical pipes with a diameter of 0.032 m, and with 0.07 and 0.20 m heated lengths, corresponding to Rayleigh numbers of 5.78×10^{10} and 1.35×10^{12}, respectively. The chimney height ranged from 0 to 1.0 m for a fixed Prandtl number of 2094. Mass transfer experiments were carried out based upon the analogy between heat and mass transfer systems. Numerical simulations were performed for several Prandtl numbers ranging from 0.7 to 2094, Rayleigh numbers from 1.93×10^7 to 5.78×10^{10}, and chimney heights from 0 to 2.0 m.

2. Theoretical background

2.1. Chimney phenomena

A chimney accelerates flow through buoyancy; the chimney acts as a shroud for the plume emanating from the heated section of a furnace [10]. The chimney height determines the acceleration of the hot plume, and the heat transfer is enhanced with the resulting increase in flow rate [11].

In the chimney, the mass flow rates are constant at all axial locations since the channel walls are impermeable and all the fluid that passes through the channel must enter from the bottom [1]. The higher, hotter accelerated fluid draws the lower, cooler fluid, and the velocity field at the heated wall becomes similar to the flow of a forced convection channel since the heated fluid rises faster than flow driven by buoyancy [12].

The heat transfer rates depend on dimensionless geometrical parameters such as the expansion ratio (ratio of duct diameter D_D to heated pipe diameter D), the extension ratio (ratio of chimney height H_D to the heated length L), and the Rayleigh number [2].

The chimney extension determines the accelerating length of the hot plume. Campo et al. [12] performed a numerical analysis of an iso-flux heated channel with an adiabatic extension, and reported that there is an optimal extension ratio. As the extension ratio increased, the temperature of the heated surface decreased rapidly. The temperature was constant beyond the optimal extension ratio. They showed that this trend indicated a state of thermal saturation, *i.e.*, further expansion of H_D/L did not have any significant bearing on the wall temperature.

Kazansky et al. [13] numerically and experimentally investigated natural convection heat transfer from a vertical, electrically heated

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Nomenclature

C	Molar concentration [mole/m^3]
D	Inner diameter of the heated pipe [m]
D_m	Mass diffusivity [m^2/s]
F	Faraday constant, 96,485 [C/mole]
g	Gravitational acceleration, 9.8 [m/s^2]
Gr_L	Grashof number ($g\beta\Delta TL^3/\nu^2$)
H_D	Height of the duct pipe [m]
h_h	Heat transfer coefficient [W/m^2 K]
h_m	Mass transfer coefficient [m/s]
I_{lim}	Limiting current density [A/m^2]
k	Thermal conductivity [W/m K]
L	Length of the heated pipe [m]
M	Molarity [mole/l]
N	Number of electrons in charge transfer reaction
Nu_L	Nusselt number (h_hL/k)
Nu_o	Nusselt number without chimney
P	Pressure [Pa]
Pr	Prandtl number (ν/α)
Ra_L	Rayleigh number (Gr_LPr)
Sc	Schmidt number (ν/D_m)
Sh_L	Sherwood number (h_mL/D_m)
T	Temperature [K]
t_{Cu}^{2+}	Transference number of Cu^2
u	Horizontal velocity [m/s]
U_x	Uncertainty of x
V	Mean velocity [m/s]
v	Vertical velocity [m/s]

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Volume expansion coefficient [1/K]
γ	Dispersion coefficient
μ	Viscosity [kg/m s]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]

plate that was placed symmetrically in a chimney of variable height, using air as the working fluid. They confirmed that a heat transfer enhancement of up to 10 times could be achieved.

The fluid near the outlet of a chimney may flow into the chimney due to the pressure difference. The amount of inflow is affected by the expansion ratio. Cold inflow at the outlet section has been shown to worsen the chimney effect by cooling the hot rising fluid [5,14].

Auletta and Manca experimentally studied a channel–chimney system to elucidate the heat transfer and fluid behaviors. They found that heat transfer in the heated channels was only weakly affected by adiabatic extensions. When the expansion ratio was greater than one, the overall heat transfer was reduced by approximately 4% since the inflow interrupted the expansion of hot plume jets at the top of the chimney [15].

The heated wall serves as a thermal pump for the ventilation of fluid beneath the chimney. Thermal pumping effects are evaluated by the mass flow rate of air through the chimney and the variation of the flow rate along the height of the chimney [13]. The thermal pumping power is capable of driving the fluid irrespective of the distributed pressure drops created by the unheated extension [12].

The natural convection of chimney systems has been extensively studied, both experimentally and numerically [16–18]. More recent trends in natural convection research have focused on finding new configurations that improve the heat transfer parameters, or analyzing standard configurations to find optimal geometric parameters for an increased heat transfer rate [2]. However, the majority of existing studies use numerical models rather than experimental data, and in most studies, the working fluid is only air. Facilities for testing natural convection in chimneys must be physically large enough to achieve a high Rayleigh number. Heat transfer experiments may also suffer from problematic heat leakage and radiation [19].

2.2. Prandtl number influence

Bejan [20] reported that if the boundary layer thickness is much smaller than the wall-to-wall spacing, the flow along one wall could be regarded as a wall jet, unaffected by the presence of the other wall. On the other hand, if the boundary layer grows to the point where its thickness is comparable to the wall-to-wall spacing, the two wall jets formed by the walls merge into a single buoyant stream rising through the chimney.

The influence on the chimney effect by the interaction of boundary layers is dependent on the value of the Prandtl number. As shown in Fig. 1, an increase in Prandtl numbers larger than one results in a thicker layer of unheated fluid being driven upward by the heated layer. However, when the Prandtl number is less than one, the thermal boundary layer is thicker than the momentum boundary layer, and the fluid flows upward through buoyancy.

2.3. Mass transfer experiments based on the analogy concept

A heat-transfer problem can be solved using mass transfer experiments based on the analogy between heat and mass transfers since the mathematical models dealing with the two phenomena are the same [20]. Therefore, heat transfer experiments can be replaced by mass transfer experiments, and *vice versa*. Table 1 presents the corresponding governing parameters. In the present work, measurements were made using a sulfuric acid–copper sulfate (H_2SO_4–$CuSO_4$) electroplating system, which enabled high Rayleigh numbers to be accurately attained by measuring the electric current. This technique has

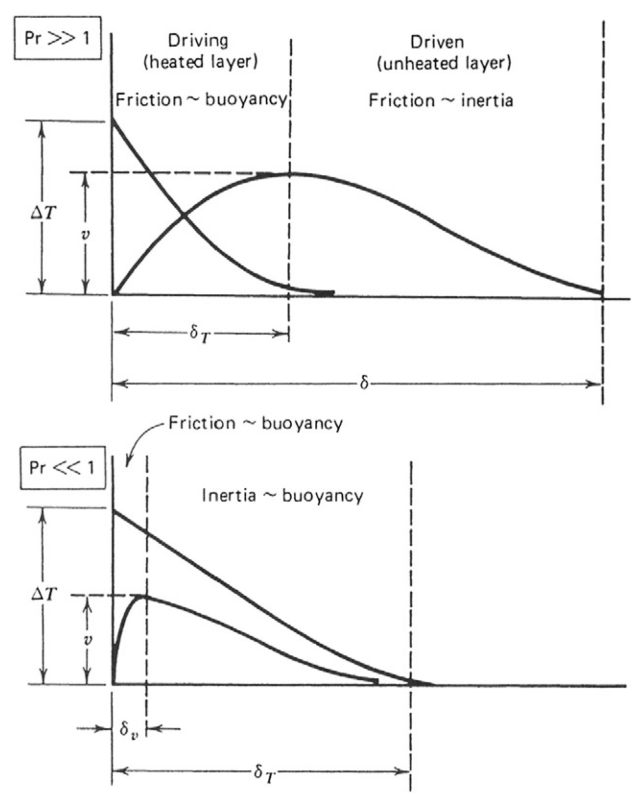

Fig. 1. Two length scales of the boundary layer flow along a heated vertical wall [20].