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Influence of a center anode in analogy experiments of long flow ducts ☆

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ABSTRACT

Experiments on chimney systems were performed using a copper electroplating system based on the analogy concept. Numerical investigations were carried out to examine the influence of an anode placed at the center of a chimney system. The chimney heights were varied for $Ra_D = 7.23 \times 10^9$ and $Sc = 2094$. As the chimney height increased, the heat transfer rates were enhanced but the enhancement rate decreased. Comparison of the numerical results with and without the anode showed different velocity and temperature profiles near the anode. However, those near the heated wall exhibited similar values. Thus, the influence of the anode was negligible at a heated wall. This study provides a theoretical background of using an anode to simulate chimney phenomena.

1. Introduction

A thermally insulated chimney attached to a vertical heated section induces an increase in the flow rate and leads to a higher heat transfer rate. Most reported studies on chimney systems have been performed numerically. Experimental studies are rare due to the high costs of large facilities and the difficulties in controlling the experimental conditions [1]. However, mass transfer experiments based on the analogy concept can be employed to overcome these difficulties. A copper–sulfate electroplating system, which is a mass transfer system, offers high Rayleigh numbers in short test facilities and exact measurements by electrical means. It is also free of experimental difficulties such as heat leakage to the external environment and radiation heat transfer [2]. In an electroplating system, the reduction of the cupric ion concentration near the cathode induces a local reduction of the fluid density compared to the surrounding fluid. The cathode serves as a heated wall and the anode serves as a cold wall [3].

When experiments are performed on chimney systems with long and narrow flow duct geometries, as shown in Fig. 1, the anode should be placed at the center of the duct. Otherwise, current measurements are very difficult [1,4,5]. However, an anode placed in the chimney induces downward flow along the anode and affects the temperature and velocity fields, both of which can bias the chimney heat transfer effects [6,7].

This study investigated the influence of an anode placed at the center of a chimney on the velocity and temperature fields. Mass transfer experiments using a copper–sulfate electroplating system were carried out. Numerical simulations using FLUENT 6.2 software were also performed for the same geometric system with and without the anode. The simulation results were compared to explore the influence of both the presence and the placement of the anode.

2. Theoretical background

2.1. Heat transfer phenomena in a chimney system

A chimney accelerates flow through buoyancy; the chimney acts as a shroud for the plume emanating from the heated section of the furnace [8]. In an ideal chimney, the flow rate is the same at every elevation due to the duct flow condition. The upper, hotter accelerated fluid draws the lower, colder fluid. The flow pattern in the heated section begins as natural convection, and becomes forced convection as the heated fluid rises [9,10].

The chimney height determines the acceleration of the hot plume. The heat transfer is enhanced with an increase in the chimney height since this increases the flow rate. However, increases in chimney height above a certain threshold do not further influence the heat transfers due to the increase in the friction loss [10]. Thus, an optimal chimney height exists.

2.2. Mass transfer experiments using an electroplating system

Heat and mass transfer systems are analogous, because the governing equations and parameters are mathematically similar [11]. Table 1 compares the dimensionless governing parameters of heat and mass transfer systems [2].

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Nomenclature

C	Concentration [mol/m^3]
D	Diffusivity [m^2/s]
D_h	Diameter of cathode (heated cylinder) [m]
D_c	Diameter of chimney [m]
F	Faraday constant, 96,485 [C/mol]
g	Acceleration of gravity [9.8 m/s^2]
Gr_D	Grashof number [$g\beta\Delta TD^3/\nu^2$]
Gr_L	Grashof number [$g\beta\Delta TD^3/\nu^2$]
h_h	Heat transfer coefficient [$W/m^2 \cdot K$]
h_m	Mass transfer coefficient [m/s]
H_c	Height of chimney [m]
I	Electric current [A]
I_{lim}	Limiting current density [A/m^2]
k	Thermal conductivity [$W/m\cdot K$]
L_h	Length of cathode (heated cylinder) [m]
n	Number of electrons in charge transfer reaction
Nu_D	Nusselt number [h_hD/k]
Nu_L	Nusselt number [h_hL/k]
Pr	Prandtl number [ν/α]
Ra_D	Rayleigh number [Gr_DPr]
Ra_L	Rayleigh number [Gr_LPr]
Sc	Schmidt number [ν/D_m]
Sh_D	Sherwood number [h_mD_h/D_m]
Sh_L	Sherwood number [h_mL_h/D_m]
T_{bulk}	Temperature of bulk
T_{wall}	Temperature of heated wall
t_n	Transference number
U_x	Uncertainty of x

Greek symbols

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

In this study, a copper–sulfate electroplating system was employed as the mass transfer system. Cupric ions move from the anode to the cathode by convection, diffusion, and electrical migration. The cupric ions are reduced on the surface of the cathode, while sulfate ions accumulate at the anode and establish an equilibrium concentration between electrical migration and mass diffusion.

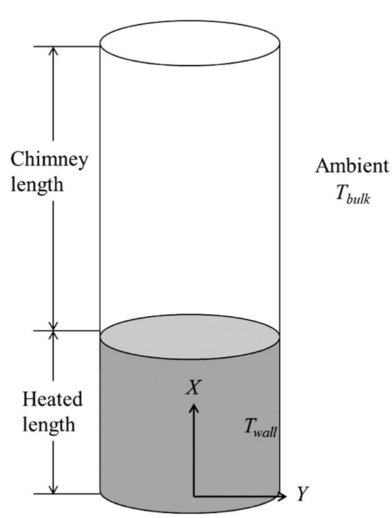

Fig. 1. Schematic diagram of a chimney system.

Levich [12] and Agar [13] proposed the application of an electrochemical system to investigate heat transfer, because electrochemical mass transfer correlations resemble those for heat transfer. Selman and Tobias [14] applied an electrochemical method to find mass transfer correlations developed under various conditions. Zaki et al. [15] also reported the use of mass transfer experiments.

In the experiments, the values for the physical properties were calculated using the relationships suggested by Fenech and Tobias [16], shown in Table 2. The values are accurate within ±0.5% at 22 °C.

2.3. Limiting current technique

Fenech and Tobias [16] experimentally studied the limiting current technique to overcome the difficulty of determining the concentration of ions at the surface of the cathode. The current between the electrodes increases with the applied potential until it reaches a plateau region, which occurs because the reduction of copper ions is much faster than the transport process. The constant current is termed a "limiting current". At the limiting current condition, the concentration of copper ions at the cathode surface can be regarded as zero. Thus, the mass transfer coefficient, h_m, can be calculated using only the bulk concentration, C_b, and the limiting current density, I_{lim} [3,17,18]:

$$h_m = \frac{(1-t_n)I_{lim}}{nFC_{bulk}}. \quad (1)$$

where F is the Faraday constant and transference number, t_n is fraction of ion engaged in the electrode reaction by electric migration among the extracted copper ions.

3. Experimental and numerical methods

3.1. Experimental apparatus

Fig. 2 contains pictures of the test facility. The cathode simulating the heated wall was placed in an acrylic pipe with an inner diameter of 0.035 m. Chimneys of different heights were connected by flanges to the cathode. A copper rod with a diameter of 0.002 m was used as the anode, which was inserted from the top of the test section using a holder. During the experiments, the test facility was immersed in a water tank of dimensions 0.18 m × 0.18 m × 1.4 m with the top open. An electric potential was applied by a power supply (VűPower, IPS18B10), and the current was measured with a dual-display multimeter (Fluke-45).

3.2. Numerical analysis

Numerical analysis was carried out using FLUENT 6.2 software [19]. GAMBIT software was used to generate the two-dimensional (2D) mesh of the chimney system. The overall domain had a width of 0.035 m and a height from 0.17 m to 1.07 m, depending on the chimney height. The height of the heated cylinder was 0.07 m. Fig. 3 shows the domain used for the calculations, which comprised heated walls, adiabatic walls, and a cold rod.

Table 1
Dimensionless groups for analogy systems.

Heat transfer		Mass transfer	
Nusselt number	$\frac{h_hD_h}{k}$	Sherwood number	$\frac{h_mD_h}{D}$
Prandtl number	$\frac{\nu}{\alpha}$	Schmidt number	$\frac{\nu}{D}$
Rayleigh number	$\frac{g\beta\Delta TD_h^3}{\alpha\nu}$	Rayleigh number	$\frac{gD_h^3}{D\nu}\frac{\Delta\rho}{\rho}$