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Transient forced convection heat transfer for nitrogen gas flowing over plate heater with exponentially increasing heat input

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ABSTRACT

The transient forced convection heat transfer of plate heater for nitrogen gas due to exponentially increasing heat input was investigated experimentally and numerically. The platinum ribbon with a thickness of 0.1 mm and a width of 4.0 mm was used as the test heater. The heat generation rate of the test heater was raised with exponential function. The inlet flow velocity was ranged from 2 to 4 m/s for the gas temperature of 313 K under the system pressure of 500 kPa. The period of heat generation rate was ranged from 45 ms to 8 s. Experimental results indicate that the surface temperature difference and heat flux increased exponentially as the heat generation rate increased through an exponential function. It was clarified that the heat transfer coefficient was divided into the two regions for the period ranging from 45 ms to 8 s. The numerical results were compared with experimental data. The numerical simulation was in agreement with the experimental data.

1. Introduction

The knowledge of transient forced convection heat transfer for various gases is important for the design of many heat transfer devices. There is a need for dynamic thermal managements of hybrid/electric/fuel cell vehicles [1]. Since thermal loads vary with the electric propulsion of the vehicles, electronic devices of vehicles require high-efficiency cooling systems. For ships, transient responses at the time of rapid load changes are also important research subjects [2]. In order to increase thermal efficiency of waste gas economizers, the optimal heat exchanger design is a key since gas flow and the temperature might change with a change of load. Moreover, transient heat transfer phenomena appear in nuclear fields. As an example of thermal transient, high heat fluxes may increase exponentially in fuel bundles due to an accident in excess reactivity [3]. Recently, it is important to reduce greenhouse gases in atmosphere for global warming. SF_6 gas, which is designated as greenhouse effect gas is used in circuit breakers for arc current interruption [4]. In order to reduce SF_6 gas, alternative gases such as high pressure nitrogen gas (N_2), mixture gas (SF_6/N_2, SF_6/He) and compressed air have been investigated [5–6]. Since these gases are heated rapidly due to the arc current interruption, it is important to predict transient response of temperature and cool them more effectively [7].

Transient heat transfer through various fluids has not been solved even though many analytical solutions and experiments concerning steady state heat transfer were reported. To the knowledge of the authors, there are only a few analytical and experimental works that are focused on the problem of transient heat transfer with an exponentially increasing heat generation rate ($\dot{Q} = Q_0 \exp(t/\tau)$, where, $\dot{Q}$ is heat generation rate, Q_0 is initial heat generation rate, t is time, and τ is period of heat generation rate (time needed for $\dot{Q}$ to increase e-fold.)). Siegel [8] analyzed the transient heat transfer for laminar flows in a parallel plate and in a tube for step changes in the wall temperature. Subsequently, Sparrow and Siegel [9] and Goodman [10] analyzed the transient heat transfer for turbulent flow in a tube. Although works have analyzed for step changes in wall temperatures, there was no experimental data verification in these works. Soliman and Johnson [11] analytically obtained the temperature change in a plate by taking into account the turbulent boundary around the plate. However, the solution for the heat transfer coefficient is 50% higher than their experimental data. In a transient experiment on water flow parallel to a cylinder, Kataoka et al. [12] obtained an empirical correlation for the ratios between the transient heat transfer coefficient and steady-state one in terms of one non-dimensional parameter consisting of period, velocity, and heater length. Liu et al. [13–18] obtained the experimental data and correlation for both parallel flow and cross-flow of helium gas over a horizontal cylinder. Since the experimental data were limited to a cylinder for the parallel flow and cross flow, they obtained the experimental

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Nomenclature

a	thermal diffusivity (m^2/s)
B	basis limit (–)
C	number of constant value for least square method (–)
c_h	specific heat of test heater (J/(Kg K))
h	heat transfer coefficient (W/m^2 K)
k	turbulence kinetic energy (m^2/s^2)
L	length of heater (m)
N	number of data (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
R	resistance (Ω)
$\dot{Q}$	heat generation rate per unit volume (W/m^3)
Q_0	initial heat generation rate per unit volume (W/m^3)
q	heat flux (W/m^2)
Re	Reynolds number (–)
S	precision index (–)
T	temperature (K)
ΔT	surface temperature difference (K)
t	time (s)
t_{95}	confidence level (–)
u	gas flow velocity (m/s)
U	uncertainty (–)
V	voltage (V)
w_1, w_2	weight coefficient (–)
σ_T	turbulent Prandtl number (–)
σ_k	effective Prandtl number for k (–)
σ_ε	effective Prandtl number for ε (–)
ε	dissipation rate (m^2/s^3)
δ	heater thickness (m)
ρ_h	density of test heater (kg/m^3)
λ	thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
τ	period of heat generation rate (s)
τ^*	non-dimensionless period (–)

Subscripts

a	average
b	bulk
e_f	effective length
f	film
h	heater
LS	least square
s	surface of test heater
t	turbulence
I	current
i	I-direction
j	J-direction
R	resistance
RSS	root sum square
T	temperature

data and correlation for horizontal cylinder and plate under various experimental conditions to clarify the effects of periods, velocities, pressure, gas temperatures and heater configurations on the transient heat transfer. Since the transient heat transfer for helium gas increased with a decrease of the period, helium gas can cool walls of circuit breaker at the arc current interruption. However, the breakdown voltage of helium gas is smaller than that of nitrogen gas [19]. Although nitrogen gas is a candidate of alternative gas for circuit breakers [5,20–21], there were no experimental data of the transient heat transfer coefficient for nitrogen gas.

In this research, the transient forced convection heat transfer for nitrogen gas flowing over a plate heater was due to exponentially increasing heat inputs was investigated experimentally and numerically. Our objectives were to obtain the transient heat transfer coefficients of nitrogen gas at various periods of heat generation rate and flow velocities; and to compare the numerical simulations with the experimental data; then to clarify the effects of the periods and velocities on the transient heat transfer.

2. Experimental apparatus and method

2.1. Experimental apparatus

Fig. 1 shows a schematic diagram of the experimental apparatus [13–18]. The experimental apparatus is composed of a gas compressor (2), a flow meter (5), a test section (6), surge tanks (3),

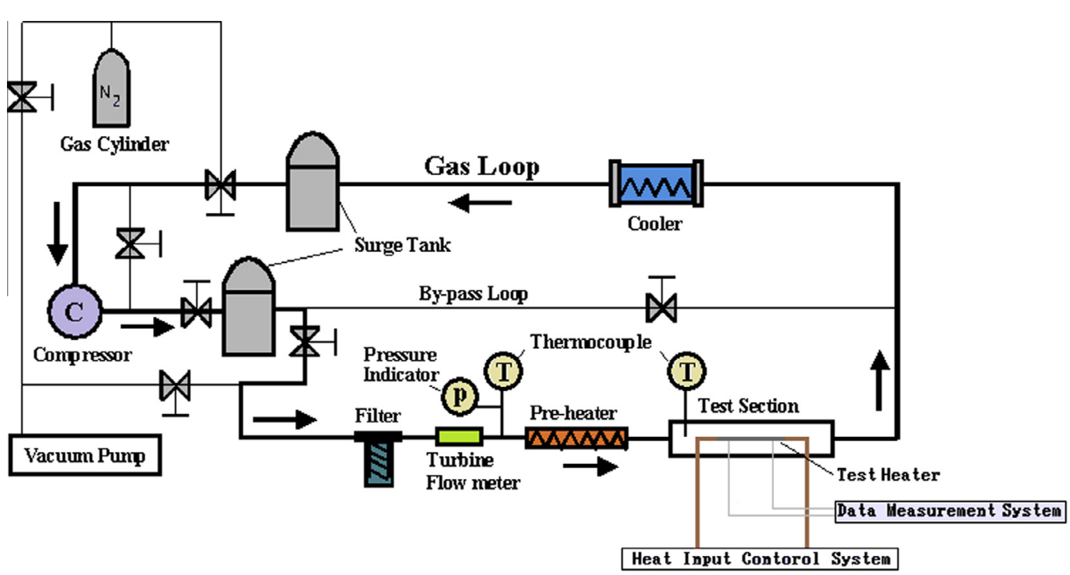

Fig. 1. Schematic diagram of experimental apparatus.