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Frequency-dependent heat transfer enhancement from rectangular heated block array in a pulsating channel flow

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Abstract

The effect of pulsating flow on convective heat transfer from periodically spaced blocks in tandem on a channel wall is experimentally investigated. The spacing l between repeated blocks varied from $l/L = 0.3$ to 0.6 where L is the block pitch. The experiments are carried out in the range of $10\,\text{Hz} < f_F < 100\,\text{Hz}$ and $0.2 < A < 0.3$. A pulsating flow is imposed by an acoustic woofer at the channel inlet and a constant heat is generated at each protruding block. The impact of the important governing parameters such as the Reynolds number, the Strouhal number and the inter-block spacing on heat transfer rate from heated blocks is examined in detail. The experimental results show that thermal transport from the blocks is greatly affected by the frequency, the amplitude of the flow pulsation, the inter-block spacing and the Reynolds number. Thermal resonance frequency which shows a maximum heat transfer coincides well with the inverse of traveling time of a fluid parcel that can be determined from the block periodicity and the Reynolds number.

1. Introduction

Extensive studies on heat transfer from a heated block array in a channel have been conducted in response to industrial demand such as electronics cooling and compact heat exchangers. For the steady flow, lots of experimental and numerical studies [1–6] showed that as fluid passed over a heated block array, the periodic redevelopment of thermal boundary layer occurred at each block and its contribution was crucial to the total heat transfer rate. Inside the inter-block region, however, heat transfer was relatively meager attributed to less flow communication of recirculating cell with the main throughflow.

In an effort to enhance convective heat transfer from such a confined recirculation zone, a heat transfer augmentation scheme adding a pulsation component to a main through-flow has been proposed in recent years. This scheme was relevant to the amplification of the flow instability inherently existed in a self-sustained oscillation regime by forced pulsation [7–12]. Using the flow

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Nomenclature

a	height of a block [mm]
A	oscillating amplitude of axial velocity
D	length of a block [mm]
G	geometry
E	heat transfer enhancement factor, Nu_p/Nu_s
f	dimensional frequency [Hz]
f_F	forcing frequency of pulsating flow [Hz]
f_n	natural shedding frequency of a block array [Hz]
f_R	thermal resonance frequency at which the resonance in heat transfer occurs [Hz]
h	half height of flow channel above the block [mm]
h_c	convective heat transfer coefficient [W/m^2 K]
H	height of flow channel [mm]
k	thermal conductivity [W/m K]
l	inter-block spacing [mm]
L	block pitch [mm]
Nu	time-averaged local Nusselt number at each block, $Nu = h_cH/k = qH/(T - T_a)k$
Nu_b	time-averaged local bulk Nusselt number at each block, $Nu_b = qH/(T - T_b)k$
$\overline{Q}$	time-averaged flow rate [m^3/s]
q	heat flux input at the heated block surface [W/m^2]
Re_H	Reynolds number, U_oH/ν
St	Strouhal number, fH/U_o
St_F	Strouhal number of inlet pulsating frequency, f_FH/U_o
St_R	Strouhal number of thermal resonance frequency, f_RH/U_o
T	local temperature [K]
T_a	inlet air temperature [K]
T_b	bulk air temperature [K]
U_c	time-averaged velocity at the channel center over the block array, $(3/2)(\overline{Q}/2hW)$ [m/s]
U_i	inlet velocity, $U_i = U_o(1 + A\sin 2\pi f_Ft)$ [m/s]
U_o	time-averaged velocity of the inlet flow [m/s]
U_p	oscillatory amplitude of inlet velocity, $U_o \cdot A$ [m/s]
W	Channel width [m]

Greek symbols

ν	kinematic viscosity [m^2/s]
τ	characteristic frequency estimated by convective time scale, $\tau = L/U_c$ [Hz]

Subscripts

G	previous study by Greiner [7]
N	previous study by Nishimura et al. [9]
p	pulsating component
s	steady-state component

pulsation, the amplified hydrodynamic instability in a shear layer substantially augmented flow mixing in a channel, and resulted in convective thermal transport enhancement. Ghaddar et al. [7,8] showed that the least stable mode existed in a periodic grooved-channel flow and heat transfer was augmented when the pulsation frequency was in tune with a specific frequency of the least stable mode, which was indicative of resonance. This resonant phenomenon in heat transfer was experimentally verified by Greiner [9]. Kim et al. [10] carried out numerical studies for the pulsating flow and the associated heat transfer from two successive heated blocks inside a channel and reported that heat transfer was enhanced by spatially enhanced flow mixing with the presence of pulsation. Nishmura et al. [11] studied fluid mixing and mass transfer in a grooved channel with different inter-block spacings. Recently, Bae et al. [12] demonstrated the resonant convective heat transfer augmentation at downstream protruding blocks by controlling time-periodic change of heat generation rate at the most upstream block in a multi-block arrangement.

Some studies [7–9] revealed that small fluid oscillation with the natural frequency of the hydrodynamic instability amplified the flow instability within a grooved channel, even at Reynolds numbers below the critical value for the onset of self-sustained oscillations, and thus enhanced heat transfer. The natural frequency was closely matched with the Tollmien–Schlichting wave for the grooved channel [7,8]. However, some previous experimental works showed that thermal resonance frequency did not always coincide with the natural frequency estimated by the hydrodynamic instability wave. Nishimura et al. [11] raised such a question that the resonance mechanism in a grooved channel was not clearly explained by the Tollmien–Schlichting wave for some cases. Therefore, there seems to be another dominant frequency which characterizes resonant heat transfer enhancement in a pulsating grooved channel flow.

The present paper examines experimentally the influence of pulsation frequency on the convective heat transfer from a heated block array as shown in Fig. 1. Based on the present experimental data, the resonant frequency for convective heat transfer enhancement will be evaluated, comparing with the results based on the previous hydrodynamic instability concept. Finally, we aim to elucidate thermal resonance mechanism from a heated block array by the flow pulsation.