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Thermal performance improvement by injecting air into water flow

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ABSTRACT

As an active Heat Transfer Enhancement (HTE) measure for design and retrofit applications by injecting airflow into liquid stream, this experimental study examines the thermal performances of upward co-current air–water flow through a furrowed narrow channel with skewed wall waves and ribs. Superficial liquid Reynolds number (Re_L) and air-to-water mass flow ratio (AW), in the respective ranges of 800–6000 and 0–0.05, are selected as the controlling parameters to specify the flow conditions tested and to devise the heat-transfer and pressure-drop correlations. Even with the presence of multi-cellar vortices in this wavy ribbed channel, the modified drift flux model is still capable of correlating the channel-wise averaged void fractions to feature the equivalent dryness factors. The various patterns of gas–liquid flow structure imaged by the computerized high frame-rate videography reveal the Re_L and AW impacts on the air–water interfacial mechanics, which assist to illustrate the corresponding heat transfer and pressure drop properties. A set of selected full-field and area-averaged heat transfer data along with the pressure drop coefficients demonstrate the improved HTE impacts at the expense of increased pressure drop penalties by airflow injections. Empirical heat-transfer and pressure-drop correlations that permit the evaluation of individual and interdependent Re_L and AW impacts on heat transfer and pressure drop coefficients are generated. With the scope of energy saving, Thermal Performance Factors (TPF) obtained at various Re_L and AW are compared with other HTE devices to enlighten the competitive advantage of this air-injection HTE measure for the present ribbed wavy channel.

1. Introduction

Parallel with the exploration of renewable energy to resolve the global warming crisis, energy saving for existed carbon emission plants that involve various heat exchangers, such as geothermal, thermal and nuclear power plants, chemical plants and ship propulsion power plants, also plays an important role for reducing fossil fuel consumption. Driven by such energy saving incentive, the development of efficient and eco-friendly HTE measures for boosting HTE benefits with convenient retrofit applications is essential. Heat transmissions for such marine applications widely deploy plate heat exchangers. With cooling applications for ship propulsion, the conveniently available seawater is often channeled through a number of parallel narrow ribbed channels in a plate heat exchanger prior to discharging back to sea. Taking the advantage of lesser pressure drops and thus the reduced pumping power consumptions, the sinusoidal wavy channels with and without ribs at static and simulated sea-going conditions were previously proposed by this research group as passive HTE elements for plate type heat exchangers [1–3]. After the early experimental and numerical studies which confirmed the noticeable HTE effects by tripping longitudinal vortices, separated flows and flow reattachments over the undulant walls in corrugated channels at $Re > 1500$ [4–6], the development of sinusoidal wavy channels for passive HTE benefits [7,8] was under constant pursuit. Within a sinusoidal wavy channel, the in-trough recirculating flow cells were agitated by increasing *Re* to trigger macroscopic fluid mixings between near-wall and core fluids by shear layer instabilities [7] and self-sustained flow oscillations [9–11]. Following the flow visualization results [11], the schematic depiction of typical flow patterns in a furrowed wavy channel is shown by Fig. 1(a). In a furrowed convergent-divergent wavy channel, the streamwise adverse pressure gradients, which repeated periodically along this type of wavy channel, caused repeated flow separations with in-bulge reverse flows and downstream reattachments [12]. The unsteady self-sustained oscillatory state gradually emerged in a furrowed channel as the flow transited from laminar to turbulent by increasing *Re*. The transitional *Re* with the onset of such self-sustained flow oscillations was geometry dependent, but are generally much less than the Reynolds numbers designed for heat exchangers [10]. Further raising *Re* from the transitional value,

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Nomenclature

English symbols

A	cross-sectional area of test channel (m^2)
a_s, bs	functional coefficients in heat transfer correlations
AW	air-to-water mass flow ratio $= \dot{m}_G/\dot{m}_L$
C_p	specific heat of liquid (water) ($J\ kg^{-1}\ K^{-1}$)
d	hydraulic diameter of test channel (m)
e	rib height (m)
f	pressure drop coefficient = $\Delta P/(0.5\rho_L U_{LS}{}^2)(d/4L)$
f_∞	reference of pressure drop coefficient for plain tube
H	channel height (m)
g	gravitational acceleration (ms^{-2})
k_f	thermal conductivity of liquid (water) ($Wm^{-1}\ K^{-1}$)
L	channel length (m)
$\dot{m}_G$	mass flow rate of gas phase (air) (kgs^{-1})
$\dot{m}_L$	mass flow rate of liquid phase (water) (kgs^{-1})
Nu	local Nusselt number = $q_f d/[(T_w - T_b)k_f]$
$\overline{Nu}$	area-averaged Nusselt number
Nu_∞	plain tube Nusselt number reference
P	rib pitch (m)
Pr	Prandtl number of liquid (water) ($\mu C_p/k_f$)
ΔP	pressure drop across test channel (Nm^{-2})
$\dot{Q}_{Air}$	volume flow rate of airflow ($m^3 s^{-1}$)
$\dot{Q}_{Water}$	volume flow rate of water flow ($m^3\ s^{-1}$)
q_f	convective heat flux (Wm^{-2})
Re_L	superficial liquid (water) Reynolds number = $\rho_L U_{LS} d/\mu_L$
S	wave-wise or rib-wise coordinate (m)
St	stanton number = $Nu/(Re_L Pr)$
T_b	fluid bulk temperature (K)
T_w	wall temperature (K)
TPF	thermal performance factor $= (\overline{Nu}/Nu_\infty)/(f/f_\infty)^{1/3}$
U_{GS}	gas (air) superficial velocity $= \dot{m}_G/(A\rho_G)^{ms^{-1}}$
U_{LS}	liquid (water) superficial velocity $= \dot{m}_L/(A\rho_L)(ms^{-1})$
V_{Gj}	gas drift flux$= 0.35\sqrt{g\rho L - \rho_G d/\rho_L}(ms^{-1})$
W	channel width (m)
X, Y	dimensionless axial and spanwise coordinate (x/d, y/d)

Greek Symbols

α	averaged void fraction across test tube
ρ_G	gas (air) density (kgm^{-3})
ρ_L	liquid (water) density (kgm^{-3})
λ	wave pitch (m)
μ_L	liquid (water) dynamic viscosity ($kgm^{-1}\ s^{-1}$)

Subscripts

AW = 0	single-phase water-flow condition
AW > 0	air–water mixture flow condition

the destabilization of thermal boundary layer replenished near-wall fluids by core fluids to boost HTE effects further. Roller vortices in free shear layers were generated to stimulate small-scale oscillations in core flow, enhance macroscopic mixings and introduce three-dimensionality in flow field [11]. Although the core-to-wall macro-mixings also developed in a corrugated wavy channel, the in-trough recirculating flows along its serpentine flow pathway were generally smaller than those in a furrowed channel. In a corrugated channel at *Re* above than the transitional value, the core flow underwent large oscillations to shift the reattachment points upstream [11]. With sufficient upstream shifts of these reattachment points, the core flow started injecting free-stream fluids into recirculating cells with simultaneous fluid-ejections from recirculating cells into the core flow, generating considerable HTE effects [11].

At turbulent conditions, the separated shear layers between the core flow and in-trough recirculation cells enhanced turbulence productions in a wavy channel. The accordingly augmented Reynolds stresses resulted in higher streamwise velocity gradients at wall and reduced the size of in-trough recirculation bubbles from the laminar counterparts; leading to the shortened axial span of low Nusselt number (*Nu*) region in the bulge of a wavy channel [13]. The peaks of intensified Reynolds stresses diminished the thickness of viscous sublayer, increased near wall temperature gradients and developed near the separation bubbles. Local *Nu* peaks emerged shortly behind the points of separation. With prevailing turbulent activities along a wavy channel, the wave amplitude and *Re* were two primary factors affecting the impacts [14]. Along with the vortex stretching and near-wall flow accelerations, the regional vortex enhancement along the up-slope of a wavy channel could be further intensified by increasing wave amplitude [14]. With large wave amplitudes, the axial *Nu* distributions were considerably affected by flow separations. *Nu* peaks constantly developed near the wavy crests where the inviscid free-stream velocities reached local maximums [13]. Acting by the up-slope vortex enhancement and the *Nu* peak at wavy crest, local *Nu* generally increased along the up-slope portion of a wavy wall within which the maximum *Nu* and friction factor emerged. The more recent endeavors successfully resolved the correlations between turbulent velocity and temperature fields over a sinusoidal wavy wall using digital particle image velocimetry (PIV) and liquid crystal thermometry (LCT) [15,16]. During streamwise convection, high-temperature, low-momentum flow structures developed near wall as fluids were partially decelerated by wall shears and heated by hot wall. While the low-momentum, high-temperature fluids surged from the undulant hot wall, the large-scale longitudinal flow structures, which carried the bulk of kinetic energy in the momentum and scalar fields over the sectional plane parallel to the channel wall, replaced the high-momentum low-temperature fluids that convected toward the wall. Such thermal fluid structures developed periodically and dynamically in spanwise direction and elongated in streamwise direction; generating three dimensional variations. Heat transfer enhancements appeared as the result of complex interactions between core fluids and boundary-layer fluids via shear layer destabilization and self-sustaining oscillations [15]. With mixed convection at elevated buoyancy levels over a wavy wall, a meandering of scalar plume induced by longitudinal flow structures was observed [16] and triggered the spanwise spreading of the mean scalar field to greatly enhance spanwise scalar transports, such as turbulent heat flux, from the isothermal scenarios. Due to the enhanced vertical transport by buoyancy interactions and the enhanced spanwise transport by the mixed-convection induced longitudinal flow structures, the momentum and energy transports were promoted from the isothermal conditions in a wavy channel [16]. Further HTE benefits were attainable by skewing the orientation of wall-wave to trip strong cross-plane secondary flows in the form of multi-cellar rolling vortices [1,2]. Along with the downstream development of these cross-plane vortical flows and the aforementioned HTE flow mechanics in a wavy channel with transverse wall waves, local *Nu* was asymptotically increased toward the periodically developed level. Wave-numbers required reaching the developed flow region with amplified HTE impacts decreased as *Re* increased, leading to upstream extension of effective HTE region. With 45° ribs installed along skewed wavy crests, the streamwise and spanwise *Nu* profiles over such wavy ribbed wall took the hybrid forms by merging