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Thermal performance of undulant narrow channel with skewed sinusoidal wall-waves and 45° ribs

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ABSTRACT

This experimental study examines the properties of heat transfer, pressure drop and thermal performance factor (TPF) of a narrow undulant channel enhanced by skew sinusoidal wall-waves and 45° ribs. Detailed Nusselt number (Nu) distributions over the wavy ribbed channel wall are generated by the steady-state infrared thermography method and examined along with the accompanying pressure drop coefficient (f) in the test Reynolds number (Re) range of 800–9000. With references to the Nusselt numbers (Nu_∞) and pressure drop coefficients (f_∞) of smooth plain tube, the area-averaged heat transfer enhancement (HTE) ratios, pressure drop augmentations (f/f_∞) and TPF for the tested undulant channel are compared with those obtained from other passive HTE devices. Empirical correlations evaluating the area-averaged Nusselt number ($\overline{Nu}$) over the undulant ribbed channel wall and the pressure drop coefficients are generated to assist design activities using this newly devised HTE measure.

1. Introduction

As a passive HTE device of relatively low pressure drop penalty, the thermal fluid phenomena in wavy channels have been extensively studied [1–15]. Pioneer studies [1–3] examined thermal performances in corrugated channels within which the longitudinal vortices, large-scale vortical circulations and flow reattachments on the undulant wall were reported as the dominant HTE mechanisms. However, the saw-tooth like corrugated channel inherits high pressure drops which neutralize the HTE effects but stimulate the research development of undulant channels with smooth wall waves [4–11]. In this regard, the recirculating flow cell in a wavy trough of a sinusoidal wavy channel became unstable to trigger the macroscopic mixing between near-wall and core fluids by shear layer instabilities [5] and the self-sustained flow oscillations [7–9]; which in turn improve the exchanges of momentum and energy in the direction normal to the channel wall. At flow conditions involving stimuli for flow unsteadiness, the eddy cells trapped in the wavy troughs start oscillating for both corrugated and convergent–divergent wavy channels, leading to augmented HTE impacts. As Re increases above than the transitional value which depends on channel geometries [8], the self-sustained oscillatory unsteady eddies emerge in a sinusoidal wavy channel and the destabilized thermal boundary layer replenishes the near-wall fluid with the core fluid. The onset of such wall-to-core mixing at high Re is accompanied with the formation of roller vortices in the free shear layer that stimulates small oscillations in core flow [9]. Such shear-layer driven mixing enhances the macroscopic momentum/energy transportations and introduces three dimensionality of flow in wavy channel [9]. Additionally, in a convergent–divergent wavy channel, the downstream flow pressures vary periodically, giving rise to streamwise adverse pressure gradients near bulges where the reverse flows develop to induce trapped vortices within the entire wavy trough [10]. Further downstream toward the convergent throat, the repeated reverse of streamwise pressure gradients triggers flow reattachments that augment local heat transfer performances. In a corrugated channel, the bulk flow travels along the serpentine pathway, experiencing the similar flow phenomena developed in a convergent–divergent wavy channel. But the trapped recirculating cell in each wavy trough of a corrugated channel is smaller than that in the convergent–divergent wavy channel. At Re above the transitional value to trigger the macroscopic eddy oscillations in a corrugated channel, the oscillatory core flow causes upstream shifts of reattachment points [9]. With large extents of upstream shift for the reattachment point, the core flow starts injecting cold fluids from the free-stream into the recirculating cell. In return, the recirculating cell ejects hot fluids to core flow simultaneously to excite the dynamic wall-to-core mixings with considerable HTE effects generated [9]. For both convergent–divergent and corrugated wavy channels, the instabilities of laminar flow move upstream toward the channel entrance as Re

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Nomenclature

English symbols

- a wave amplitude (m)
- d channel hydraulic diameter (m)
- e rib height (m)
- f pressure drop coefficient = $\Delta P/(0.5\rho W_m^2)(d/4L)$
- f_∞ fanning friction factors in plain tube (laminar flow = $16/Re$, turbulent flow = $0.079Re^{-0.25}$)
- H channel height (m)
- k_f thermal conductivity of fluid ($Wm^{-1}\,K^{-1}$)
- L channel length (m)
- l rib land (m)
- Nu local Nusselt number = $q_f d/\{k_f(T_w-T_b)\}$
- $\overline{Nu}$ area-averaged Nusselt number over undulant ribbed wall
- Nu_∞ Nusselt number reference (laminar flow = 48/11, turbulent flow = $0.023Re^{0.8}Pr^{1/3}$)
- P rib pitch (m)
- ΔP pressure drop between channel entry and exit (Nm^{-2})
- q_f convective heat flux (Wm^{-2})
- Re Reynolds number = $\rho W_m d/\mu$
- S Wave-wise coordinate (m)
- S_p peripheral length of transverse section of test channel (m)
- S_R length of skewed wall wave or rib (m)
- T_b fluid bulk temperature (K)
- T_w wall temperature (K)
- TPF Thermal performance factor = $(Nu/Nu_\infty)/(f/f_\infty)^{1/3}$
- W channel width (m)
- W_m mean flow velocity at entrance of test section (ms^{-1})
- x, y coordinates (m)

Greek symbols

- α Attack angle of wall waves and skew ribs (deg)
- ρ Density of fluid ($kg\,m^{-3}$)
- μ Fluid dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
- λ Wave pitch (m)

increases [11]. As the bulk stream interacts more intensively with the recirculating cells in the serpentine passage of corrugated wavy channels, the traces of significant mixing emerge further upstream than those in convergent–divergent channels [11].

For turbulent wavy channel flow, the promoted turbulence production by separated shear layers augments the shear stresses in the layer between the recirculation bubble and turbulent core; which in turn results in the higher streamwise velocity gradients at wall and reduces the size of recirculation bubble compared to laminar flow and leads to the shortened axial span of minimum *Nu* in the bulge of a wavy channel [12]. Local peaks of Reynolds stresses are developed near the separation bubble to diminish the thickness of viscous sub-layer and increase the gradients of wall temperature so that the local *Nu* peak emerges shortly behind the point of separation. The wave amplitude among the various geometric parameters those define the undulant channel wall and *Re* are the primary factors those determine the turbulent complexities affected by undulant walls and therefore the HTE impact for turbulent wavy channel flow [13]. In this regard, vortex enhancement over the up-slope region of a wave pitch is identified as the process of vortex stretching accompanying by the near-wall flow acceleration, together which the vortices are more intensified when the wave amplitude is increased [13]. With large wave amplitudes, the streamwise *Nu* distribution is considerably affected by the appearance of flow separation with the *Nu* peaks developed near the wavy crest where the inviscid free-stream velocity is maximum [13]. Locally high *Nu* region generally appears along the up-slope portion of each wall wave over which the maximum *Nu* and friction drag emerge [13]. A set of comprehensive experimental works with the attempt to resolve the turbulent velocity and temperature fields over sinusoidal wavy walls was carried out using digital particle image velocimetry (PIV) and liquid crystal thermometry (LCT) [14,15]. While the low-momentum high-temperature fluids surge from the heated wavy wall, the large-scale longitudinal flow structures carrying the bulk of kinetic energy in the momentum and scalar fields over the sectional plane parallel to the wall wave replace the high-momentum low-temperature fluids which convect toward channel wall. High-temperature low-momentum flows are locally developed when fluids are partially decelerated by wall shears and heated by the hot wall during streamwise convection. Such flow structures involving complex momentum and energy transportations are periodic in spanwise direction and elongated in streamwise direction; which are three dimensional. HTE benefits for turbulent wavy channel flows are the result of complex interactions between core fluids and boundary layers through the shear layer destabilization and self-sustaining oscillations [14]. By raising buoyancy levels to the conditions of mixed convection, a meandering of the scalar plume induced by longitudinal flow structures is observed in wavy channel [15], which causes spanwise spreading of mean scalar field. Therefore the spanwise scalar transport, such as turbulent heat flux, is considerably enhanced from the isothermal condition. Due to the enhanced vertical transport driven by buoyancy forces and the improved spanwise transport caused by the mixed-convection induced longitudinal flow structures, the momentum and energy transports can be improved from the isothermal conditions for mixed convective wavy channel flows [15]. While the previous works for laminar [1–11] and turbulent [12–15] wavy channel flows have extensively examined the impacts of wave pitch, wave amplitude and phase shift between two opposite wall waves on thermal transport properties of undulant channels with **transverse** wall waves, a set of recent experimental [16] and numerical [17] studies examined the detailed *Nu* distributions, pressure drops [16] and flow structures [17] in a undulant channel with **skewed** sinusoidal wall waves. In convergent–divergent channel with skewed sinusoidal wavy walls, the skewed wall waves trip strong cross-plane secondary flows in the form of two-pair rolling vortices in each wavy trough. The sectional near-wall flows are confluent at one sidewall and subsequently merged into the strong skewed core-stream impinging onto the other sidewall. Accompanying with the shear layers induced by the sectional vortices, high turbulent kinetic energies emerge along the perimeter of undulant wall with spanwise decay. Local peak of turbulent kinetic energy consistently develops at each crest of wall wave. The cross-plane secondary flows, which direct the cold core-fluid toward the obtuse sidewall and washes the heated wavy perimeter, together with the wave-wise decay of turbulent kinetic energy over the undulant channel wall, generate the wave-wise *Nu* decay over the wavy wall [17]. In view of the streamwise transport phenomena in the undulant channel with skewed wall waves, the high peaks of turbulent kinetic energy at the wave crests and the increased streamwise fluid velocities through the throat of the furrowed channel generate *Nu* peak along each skewed throat. Accompanying with the downstream development of the complex three-dimensional vortical flows in the undulant channel with skewed sinusoidal wall waves, the streamwise *Nu* variation is asymptotically increased