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Convective heat transfer investigation of acoustically excited flow over an isolated rib obstacle

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ABSTRACT

The research effort investigates the aero-thermal ramifications of acoustically excited turbulent reattaching shear flow in the wake of an isolated fence obstacle. In order to contrast the effectiveness of traveling and standing sound wave excitations towards surface heat transfer modulation, the flow is stimulated with forcing frequencies and amplitudes, in the ranges of 70–270 Hz (St = 0.1–0.38) and 103–131 dB respectively. Along with local static pressure measurements, the consequent convective heat transfer distributions are quantified by liquid crystal thermometry. Subjected to a standing wave (resonance conditions) within a conductive Strouhal regime in the St = 0.17–0.22 range, the separated flow behind the rib is observed to be significantly affected. This is evidenced by size reduction in the time averaged reattachment length of up to 37%. The ensuing local heat transfer enhancement is ~25%. Conversely, when the flow is excited with acoustic frequencies which do not correspond to resonances (traveling wave forcing), the local heat transfer distributions remained unchanged; however, limited variations in local static pressure are observed. For conditions that yield improved thermal performance, a minimum source amplitude threshold (~121 dB) is found; above this level, the aero-thermal effectiveness of the forcing rises monotonously with increased sound pressure. Even under thermally favorable excitation conditions, the integral pressure drop penalty (total net loss) remains invariant.

1. Introduction

Active and passive means of flow control are commonly employed in a broad range of applications towards deliberate modification of laminar and turbulent aerodynamic phenomena, including control of transition, boundary layer separation, shear-layer instability and flow reattachment [1,2]. A well-established approach is the introduction of small amplitude periodic disturbances to the flow. Perturbations are induced either globally (e.g. acoustic) or locally (synthetic jets, mechanical flaps, plasma actuators) [1]. The common concept underlying these flow control strategies is the deliberate manipulation of downstream shear flow evolution. Owing to its fundamental nature, flow control over a backward-facing step has received significant attention in the research community [3,4].

1.1. Rib roughened flow field

The isolated rib obstacle, comprising of a forward and rearward step, represents a generic/simple geometry incorporating various structures present in complex separating and reattaching flows. Internal passage flow over a fence is driven by the characteristic sequence of an abrupt contraction, followed by a sudden expansion. The obstacle's potential effect on the upstream flow leads to an initial acceleration and deviation away from the near wall. Hence, the free shear layer formation is initiated upstream of the fence. A prominent flow separation region in the wake of the rib dominates the flow field. In Fig. 1, time-averaged PIV streamlines and streamwise velocity magnitudes at $\mathrm{Re}_H = 12.000$ and BR = 30% show that the shear layer has the effect of bounding the low-momentum vortex cell atop the rib and confining the flow recirculation bubble in the wake of the fence. Shear layer impingement on the bottom wall marks the point of flow reattachment x_R, in the vicinity of which local maximum heat transfer x_{max} occurs [5]. Downstream, the flat plate boundary layer redevelopment is initiated.

1.2. Shear layer dynamics

The physical processes associated with the initial free shear region directly downstream of the step resembles a plane mixing layer - flow between two parallel streams at different velocities [2,7]. The mixing layer dynamics are governed by shear-induced vorticity and turbulence. As instability waves swirl into vortices, they give rise to spanwise-correlated coherent structures [8–11].

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Nomenclature

Symbol	Description
λ	[nm] sound wavelength
a	[m/s] air speed of sound
D_h	[m] channel hydraulic diameter
f	[Hz] sound frequency
h	[W/m^2 K] heat transfer coefficient
H	[m] fence height
k	[W/mK] air thermal conductivity
l	[m] characteristic length scale
M	[–] mach number
p	[Pa] pressure
Nu_D	[–] Nusselt number $[h(x,y)\cdot D_h/k]$
Re	[–] Reynolds number
St	[–] Strouhal number $[f\cdot H/U_\infty]$
SPL	[dB] sound pressure level
T	[K] temperature
x,y	[m] axial, lateral direction
u	[m/s] axial velocity

Abbreviation

BFS	backward-facing step
BR	channel blockage ratio
TLC	thermochromic liquid crystal

Subscript

0	acoustic source
∞	freestream conditions
D	hydraulic diameter based
H	step height based
max	maximum heat transfer
R	flow reattachment

Developing into sequential vortex pairing interactions, the growing scales asymptotically approach the local mixing layer thickness [11,12], and control the spreading rate as well as the entrainment of momentum.

These mechanisms also apply to the reattaching free shear layer, a consequence of flow separation over the fence [13]. Further downstream, the shear layer curves downward, followed by consequent impingement onto the wall. Beyond the flow reattachment region, vortex merging is inhibited due to the bounding surface [14–16]. However, due to persistence of large-scale coherent structures in the stream, the redevelopment of the conventional boundary layer is delayed [15,16].

1.3. Shear layer modulation

In literature, it has been observed that the shear layer dynamics can be strongly affected by periodic forcing via mechanical flaps, oscillating jets, acoustic excitation etc. In a broad range of conducive frequencies (typically reported in form of local Strouhal numbers), periodic forcing entails higher spreading rates with altered velocity profiles due to stimulation and organization of the vortex merging process. In the scope of reattaching free shear layers, this enhanced transverse momentum entrainment and mixing can result in an earlier reattachment and narrowed recirculation region [4,17,18].

In a detailed study of the forced plane mixing layer, Ho and Huang [9] ascertained frequency ranges conducive to higher spreading rates to be determined by the ratio of the shear layer natural instability frequency and the excitation frequency. Forcing at an integer subharmonic of the vortex passage frequency was found to be effective towards the vortex merging and mixing layer thickness control. The subsequently increased spreading rates were induced by a collective interaction that bypasses sequential pairing stages and merges multiple vortices simultaneously. In a

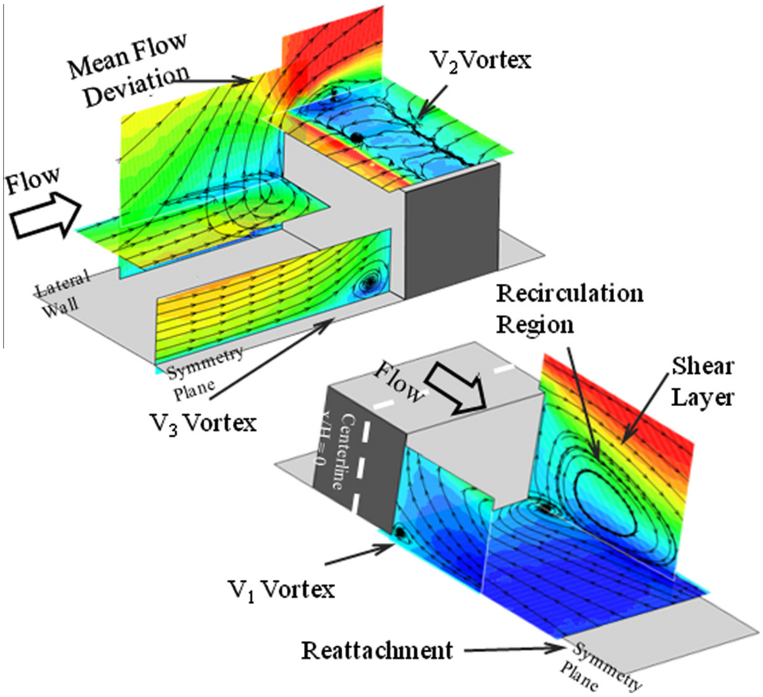

Fig. 1. Representative time-averaged fence-flow field at BR = 0.3, Re_H = 12,000; reproduced from [6].