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Flow and heat transfer measurements in a planar offset attaching jet with a co-flowing wall jet

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ABSTRACT

Measurements were performed to characterize the flow, mean skin friction, and heat transfer rate in flows consisting of a turbulent planar jet with Reynolds number of approximately 42,000 offset one jet height above a wall and a co-flowing wall jet with an initial height 0.18 times the offset distance (H_s). The results were compared to previous measurements for flows with similar offset jets and a co-flowing wall jet with initial height 0.5 times the offset distance. Low velocity wall jets in both geometries were quickly entrained into the offset jet increasing the attachment length of the offset jet and reducing the turbulent fluctuations and the heat transfer rate in the near field of the attaching jet. These changes increased with the mass flow rate of the wall jet as less mass is recirculated upstream from the attachment region. Higher velocity wall jets in both geometries initially remained attached to the wall causing a recirculation region to form between the jets that induce periodic motions that significantly increase the wall normal turbulent fluctuations in the flow. The periodic motions in the flows with the smaller wall jets significantly increased the pressure fluctuations on the wall below the near field flow and enhanced the heat transfer in this region. This differed from the results for the offset jet with the larger co-flowing wall jet where the flow fluctuations did not have a significant effect on the wall pressure fluctuations and the heat transfer below the flow. The difference in the effect of the periodic motions for flows appears to be due to differences in the forcing of the offset jet by the periodic motions and differences in the interaction between the recirculation region and the wall due to the height and mass flux of the wall jets.

1. Introduction

Turbulent offset wall-attaching planar jets, formed when a planar jet develops above a nearby surface, are used in a range of cooling applications. The entrainment into the jet causes the flow to attach to the surface after which it transitions to a wall jet flow [1–6]. The development of offset attaching jets are modified in some cooling applications, including blown film manufacturing [7], by adding a co-flowing wall jet below the offset jet. The addition of a low velocity co-flowing wall jet, typical of blown film manufacturing applications, increases the attachment length of the offset jet and reduces the fluctuations where the flow interacts with the wall [8–10]. A similar result was observed for offset jets with co-flowing wall jets used for waste water applications [11] and for radial offset attaching jets with air injected in the corner [12–14].

The development of an offset jet with a co-flowing wall jet changes as the velocity of the co-flowing wall jet increases [10,11]. Low velocity wall jets are quickly entrained into the offset jet increasing the attachment length of the offset jet, as noted previously. Higher velocity wall jets develop along the wall causing a recirculating region to form between the co-flowing jets before they merge downstream of the recirculation region. A separation bubble forms below the wall jet for moderate velocity wall jets, but higher velocity wall jets remained attached to the wall. The offset jet can also be entrained into the wall jet with only a modest effect on the wall jet for very high velocity wall jets [11]. The development of the large-scale structures in the offset jet with low velocity co-flowing jets is similar to those in an offset attaching jet [15]. The formation of the recirculation region between the offset jet and higher velocity co-flowing wall jets results in periodic structures in the neighboring shear layer of the offset jet [15–17]. These periodic motions, which appear to be associated with the recirculating flow or wake region between the jets [15], cause a significant increase in the wall normal velocity fluctuations.

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Nomenclature

H_c	height of the splitter plate between the two jets, m
H_s	offset distance from lower edge of the upper jet to the wall, m
H_j	height of the upper jet, m
H_j'	height of the lower jet, m
C_f	skin friction coefficient, $2\tau_w/\rho U_o^2$
C_P	static wall pressure coefficient, $2(P-P_\infty)/\rho U_o^2$
$C_{p'}$	fluctuating wall pressure coefficient, $2p'/\rho U_o^2$
F_{vv}	spectrum of the vertical fluctuating velocity, m^2/s
f	frequency, Hz
h	convective heat transfer coefficient, W/m^2K
$\dot{M}$	momentum flux of the upper jet per unit width, kg/s^2
$\dot{M}'$	momentum flux of the lower jet per unit width, kg/s^2
$\dot{m}$	mass flux of the upper jet per unit width, kg/ms
$\dot{m}'$	mass flux of the lower jet per unit width, kg/ms
P	static wall pressure, Pa
p'	RMS value of the fluctuating wall pressure, Pa
Re	Reynolds number of the upper jet, U_oH_j/ν
Re'	Reynolds number of the lower jet, $U_o'H_j'/\nu$
St	Stanton number, $h/\rho c_pU_o$
U	time averaged stream-wise component of the local velocity, m/s
U_o	cross-sectional averaged mean velocity of the upper jet at the exit, m/s
U_o'	cross-sectional averaged mean velocity of the lower jet at the exit, m/s
u'	RMS value of the stream-wise component of the velocity fluctuations, m/s
$\overline{u^2}, \overline{v^2}$	time averaged Reynolds normal stresses, m^2/s^2
$\overline{uv}$	time averaged Reynolds shear stress, m^2/s^2
V	time averaged vertical component of the local velocity, m/s
v'	RMS value of the vertical component of the velocity fluctuations, m/s
X_r	mean attachment length, m
x	spatial coordinate in the stream-wise direction, m
y	spatial coordinate in the vertical direction, m
z	spatial coordinate in the cross-stream direction, m
ε	emissivity
ν	kinematic viscosity of air, m^2/s
ρ	density of air, kg/m^3
ρ_{pu}	correlation coefficient of the fluctuating wall pressure and the stream-wise fluctuating velocity
ρ_{pv}	correlation coefficient of the fluctuating wall pressure and the vertical fluctuating velocity
τ_w	wall shear stress, Pa

The addition of the co-flowing wall jet below the offset jet also affects the heat transfer rate to the flow. The heat transfer rate to offset wall-attaching planar jet flows increases to a maximum near the attachment point before decreasing as the flow transitions to a wall jet flow [18,19]. The addition of a low velocity co-flowing wall jet below the offset jet decreases the heat transfer rate below the recirculating flow region and the region where the offset jet interacts with the wall [10]. Gao et al. [10] found that the heat transfer rate to offset jets with higher velocity wall jets also decreases over much of the near and intermediate field for the geometry they considered despite the increase in the velocity fluctuations associated with the formation of the recirculation region between the jets. There was an increase in the heat transfer rate near the wall jet outlet but the magnitude and extent of this increase was modest. Vishnuvardhanaro and Das [20] found evidence of heat transfer variations in the near field of $k-\varepsilon$ simulations of co-flowing offset and wall jets that they attributed to oscillations in the near field associated with the recirculation region between the jets. Their focus was on the heat transfer in the intermediate and far field so they did not examine the cause of these variations in detail. The variations they observed appear similar those observed by [10] that were due to the transition from the near exit wall jet region to the attaching region of the offset jet. Thus, the effect of the periodic motions on the heat transfer rate to the flow is unclear.

Gao et al. [10] did find that the wall pressure fluctuation below the offset jet and co-flowing higher velocity wall jets were lower than those for an offset jet over most of the near field indicating that the fluctuations associated with the recirculating region between the jets did not have a large effect on the flow near the wall for their geometry. Gao and Ewing [15] reported pressure spectra for the same offset jet with a smaller co-flowing wall jet in order to examine if the periodic motions were associated with the recirculating region. The periodic motions for the higher velocity wall jets in that geometry did appear to cause significant periodic pressure fluctuations on the wall below the co-flowing jets suggesting the fluctuations were affecting the flow near the wall. The development of the flow and the heat transfer in the offset jet with the smaller co-flowing wall jet were not considered. The objective of this investigation was to characterize the flow and heat transfer for that geometry. The experimental facility and techniques used in this investigation are outlined in the next section. The measurements of the flow field and heat transfer are then presented and compared to those of [10]. The results show a significant difference in the effect of the fluctuations associated with the recirculating region on the heat transfer and flow near the wall in this geometry. The causes of these differences are examined and discussed.

2. Experimental methodology

The measurements were performed using the co-flowing jet flow facility used in [10,15] that could be configured for flow measurements, skin friction measurements, and heat transfer measurements as shown in Fig. 1. The facility and measurements techniques are reviewed here for completeness. Air from a variable speed blower flowed into upper and lower settling chambers that included layers of foam and perforated plates for flow conditioning. The flow then entered an upper channel with a height (H_j) of 3.8 cm and length of 81 cm and a lower channel with a height (H_j') of 0.7 cm and length of 50.8 cm. The height of the lower channel was 1.9 cm in [10]. The flow exiting the channels developed over a 1.8 m long plate mounted parallel to the channel walls. The bottom wall of the upper channel was 3.8 cm above the plate, while the bottom wall of the lower channel was flush with the plate as in [10]. The facility had a width of 74 cm and included approximately 1 m high walls on either side of the facility and a similar height wall above the channel exits.

The velocity field was measured using single and cross hot-wire probes (wire diameters of 5 μm and lengths of 1 mm and 1.5 mm respectively) and an in-house anemometry system. The hot-wire probes were calibrated in a separate round jet with a uniform exit velocity profile and then mounted on a computer controlled