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Research Paper

Heat transfer distribution and shadowgraph study for impinging underexpanded jets

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ABSTRACT

In the present study, the influence of impinging underexpanded jets on local heat transfer is studied for nozzle pressure ratio (NPR) ranging from 2.4 to 5.1. To measure the local temperature distribution, a thin metal foil technique with Infrared camera is used. The adiabatic wall temperature is taken as the reference temperature for calculating local Nusselt number and recovery factor. The flow structure distributions captured with the shadowgraph technique are compared with the local Nusselt number and recovery factor distributions. Shadowgraph images show that the shock structure in the flow region plays an important role in governing the local heat transfer distribution over the plate. To propose a generalized correlation for local heat transfer for underexpanded jets, three contoured nozzles of exit diameter of 3.6 mm, 5.67 mm and 8.37 mm are studied. Proposed correlations for the local heat transfer show good agreement with the experimental results for larger nozzle to plate distances.

1. Introduction

Impinging turbulent jets have number of applications like in manufacturing industries - drying of objects, cooling or heating of surfaces, in aviation – vertical landing and takeoff aircraft, furthermore in defense and space technologies - missile or shuttle exhaust. The profile of the device from which these jets originates depends on applications, available space and cost of manufacturing. In most of the applications, the working fluid is at a higher pressure than the ambient. In such case the fluid expansion takes after jet originates from nozzle. These under-expanded jets have different flow structure than the subsonic compressible jets due to presence of shocks. These shocks significantly influence heat transfer in limited impingement area. The strength of the shocks depends upon nozzle pressure ratios (NPR), jets diameter, nozzle to plate distances. There are many prior studies on underexpanded jets available which focus on the influence of flow device design and Mach number. However, most of these studies are concerned with flow visualization and numerical simulation to understand the flow physics. Few studies are concerned with heat transfer aspects of underexpanded jets. In the present study, attempt is made to correlate the heat transfer with flow structure visualization of underexpanded jets.

It is essential to understand the jet behavior with different initial conditions by studying the heat transfer from jet impingement. Yuceil and Otugen [1] and Yuceil et al. [2] studied under expanded free jet for nozzle pressure ratios ranging from 1 to 20 and Mach number varying from 1 to 3, by measuring centerline velocity decay rates and PIV analysis. A correlation is proposed for calculation of Mach number, jet diameter, density for a jet under fully expanded condition. Heat transfer from impinging underexpanded jets has been studied by many authors thoroughly in various experimental studies. In most of these studies, fluid dynamics was studied by capturing shadowgraphs and Schlieren images, showing shock structures for a wide range of pressure ratios. Crist et al. [3], Henderson [4], Donaldson and Snedeker [5] and Donaldson et al. [6], Lamont and Hunt [7,8] provided comprehensive study to understand influence of underexpanded jets for various boundary conditions. From all these studies, it is conclusive that the flow structure is unaffected from specific heat ratios, nozzle geometry and absolute pressure. Lamont and Hunt [8] suggested a correlation for pressure distribution for under-expanded jets impinging on inclined and perpendicular plates.

Meola et al. [9] investigated the jet's instability in terms of adiabatic temperature and the pressure for the compressible flow. They found that Mach number of around 0.7 is the critical Mach

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Nomenclature

A	exit area of the nozzle, m^2
C_p	specific heat of air at constant pressure, kJ/kg K
C_d	coefficient of discharge
c	velocity of sound, m/s
D	diameter meter of the supply pipe, m
d	diameter of the nozzle, m
E	enhancement factor
h	heat transfer coefficient, W/m^2 K
I	current, A
k	thermal conductivity of air, W/m K
l	length of pipe, m
M_D	design Mach number, M = v_e/c
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, $\left(\frac{hd}{k}\right)$
Nu_o	Nusselt number at the stagnation point
NPR	Nozzle pressure ratio (P_s/P_∞)
P_e	theoretical nozzle exit pressure, Pa
P_s	supply pressure, Pa
P_∞	ambient pressure, Pa
p	perimeter, m
Pr	Prandtl number, ($\mu C_p/k$)
q	heat transfer rate, W/m^2
q_{conv}	heat carried out by convection from impinging jet, W/m^2
q_{nat}	heat carried out by convection from back side of plate, W/m^2
q_{joule}	total heat supplied, W/m^2
q_{loss}	heat loss by radiation and convection from the plate, W/m^2
$q_{rad(b)}$	heat loss by radiation from the back side, W/m^2
$q_{rad(f)}$	heat loss by radiation from the front side, W/m^2
u_e	velocity at nozzle exit calculated theoretically for choked flow, m/s
R	recovery Factor
Re	Reynolds Number, $(\rho v_e d/\mu = 4\dot{m}/\pi\mu d)$
r	radial distance from the stagnation point, m
T_j	jet temperature, K
T_{aw}	adiabatic wall temperature, K
T_d	jet dynamic temperature, K
T_e	theoretical fluid temperature at nozzle exit, K
T_w	wall temperature, K
T_0	jet total temperature, K
v_e	exit velocity, m/s
V	voltage, V
z	nozzle to plate distance, m

Greek symbols

γ	specific hest ratio
ρ	supply density of fluid, kg/m^3
ρ_e	density of fluid at nozzle exit calculated theoretically ($\rho_e = P_e/RT_e$), kg/m^3
μ	viscosity of fluid, Pa·s

number, beyond which instability is invariably present in the jet. Yaga et al. [10] carried out experimental and numerical analysis for the circular (d = 10 mm) and rectangular nozzles (aspect ratio of 3) for under-expanded jets (pressure ratios of 3 and 4.5). It is concluded that the total temperature is a function of total pressure and nozzle to plate distance (z/d). Kim et al. [11,12] and Yu et al. [13] studied the heat transfer due to under-expanded supersonic and sonic jets issued from the convergent- divergent nozzle and convergent nozzle for a wide range of the nozzle pressure ratios from 2.84 to 8.62. The surface pressure and adiabatic temperature measurement was carried out along with the visualization of shock structures. This study was focused on the heat transfer augmentation at the stagnation point and at the jet periphery for smaller separation distances. It was found that turbulence diffusion from the shear layers around the jet edge region induces higher heat transfer rates while existence of low temperature region along the jet edge and at the stagnation point attributes to vortex induced temperature separation. Katanoda et al. [14], Rahimi et al. [15] and Ramanujachari et al. [16] reported experimental result for velocity, pressure drop measurements and shadowgraph for full-expanded and under-expanded impinging jets from axisymmetric supersonic nozzles for Mach number of 1.5 and 5.1. The important conclusion of this work is that the usual method of representing Nusselt number as a function of Reynolds number is inadequate for compressible flows where the dimensional analysis shows that the nozzle Mach number or pressure ratio may also be included. However, they didn't suggested any correlation.

Ewan and Moddie [17] carried out investigation to study flow structure and velocity profile of under-expanded jets. They introduced analytical model to represent the decay of axial velocity from underexpanded sonic jets. Experiments were carried out using shadowgraphs and laser doppler anemometry to determine the near field jet structure and the axial velocity distribution for the complete field over a range of exit nozzle diameters, exit pressure ratios and jet gases. Inman et al. [18] interpreted the surface pressure profiles using the planar laser-induced fluorescence, which also exhibited the flow structures for the underexpanded supersonic and sonic, free and impinging jets issued from convergent and convergent divergent nozzles. It was concluded that the formation of recirculation region depends upon nozzle to plate distance and nozzle pressure ratio. Limaye et al. [19,20] compared underexpanded jet originated from two contoured nozzle and standard orifice for different NPR and z/d. It is inferred from these study, that heat transfer increases about 25% in case of orifice compared to contoured nozzles. Yu et al. [21] carried out experiments to visualize and analyze under expanded free jets in the case of IC engine injection application. They introduced relations to find mach disk location for under-expanded jets. Pressure distribution and heat transfer distributions were correlated in these studies. Suzuki et al. [22] studied fluid flow structure and oscillations of under-expanded impinging jets. Schlieren photographs were used to visualize fluid flow. Mitchell et al. [23] and Buchmann et al. [24] conducted 3D particle tracking velocimetry for supersonic impinging jets. They reported that the particle velocity and impingement angle are affected by the gas flow, which is in a way depending on the nozzle pressure ratio and stand-off distance. Higher pressure ratios and stand-off distances lead to higher impact velocities and larger impact angles.

The literature on underexpanded jets highlights that there is a need for correlations on heat transfer for underexpanded jets to help design engineer to predict the Nusselt number over the surface. Hence, the proposed objectives of this study are as follows-

- To measure the local Nusselt number and recovery factor distribution for the under-expanded jets.
- To capture shock structure over the smooth plate at different nozzle pressure ratios (NPR) by shadowgraph imaging and to correlate this with heat transfer.