Review on Thermal Characteristics of Jet Impingement

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Abstract: Jet impingement heat transfer is an interesting flow configuration to study because of its industrial as well as fundamental significance and it has maximum heat transfer rate.The current work studies the various researches conducted in experimental and computational studies on different physical and computational aspects of jet impinging flows. The study also includes study of various parameters like flow confinement, nozzle shape, jet to plate spacing and Reynolds number. Various computational approaches, such as, RANS, LES, DNS and hybrid models, that are used to study the jet impingement heat transfer, with their complexities and boundary conditions, have been reviewed.

Keywords: Jet Impingement, Turbulence, LES.

I. INTRODUCTION

Direct gas flame impingement heating using hydrocarbon-air flame is employed in a wide range of industrial heating processes because of rapid and high heating rates. These include shaping of glasses, heating water walls in a boiler furnace, heating metal bars and billets, melting of scrap materials. The major disadvantage of flame impingement heating is the non-uniformity of the heat flux near the stagnation point. The heat transfer due to the impingement of a flame on a target solid surface depends upon the flame structure, the temperature field in the near vicinity of the plate and both convective and radiative properties of the constituent species of the flame.

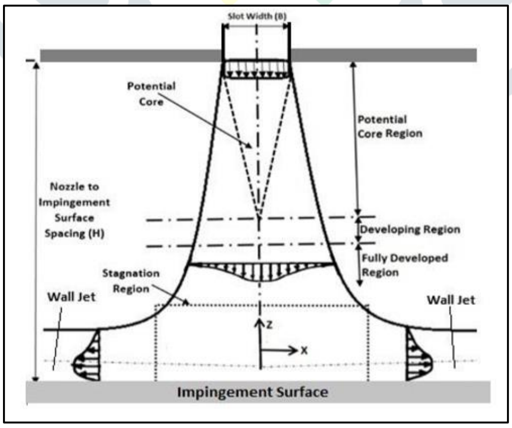

Figure 1: Different regions of jet impingement flow

The flame temperature is influenced by the flow field of the impinging jet which comprises three characteristic regions, namely, free jet region, stagnation region and wall jet region

II. LITERATURE REVIEW

Baydar and Ozmen [1] experimentally and numerically obtained the mean velocity, pressure distribution and turbulence intensity for Re ranging from 30000 to 50000 and H/D 0.2 to 6. Uncertainties involved in experimental results obtained were +2% in Re, +5% in axial velocity, +6% and +4% in turbulent velocities (u' and v'), and +1% in the pressure measurements at the impingement plate. They concluded that turbulent intensity, heat transfer coefficients and sub-atmospheric region were linked together and found the predictions using the standard k-ε model to be in best agreement with their experimental results for moderate H/D values.

Fattah [2] experimentally and numerically studied a 2-D circular jet impingement flow without any cross flow. He considered jet Re from 95000 to 224000, H/D 3 to 12, jet angle 00 to 200 and nozzle to nozzle centerline spacings (l/D) of 3, 5 and 8. The accuracy in wall static pressure measurement was +3% and in temperature reading of +0.50C. He observed a secondary stagnation point between the jets and a decreased pressure at this point by increasing the jet angle or decreasing Re.

Sagot et al. [3] experimentally and numerically studied the heat transfer configuration for a round jet impingement on a flat plate maintained at a constant wall temperature. They observed that the SST k-ω turbulence model performed well when local Nu was compared with the experimental data. Numerical results obtained with a constant wall temperature applied at the impingement wall were found to be in good agreement compared to a constant heat flux condition.

Öztekin et al. [4] experimentally and numerically investigated the hydrodynamics of a slot jet impingement on concave flat surfaces. They carried out experiments for Re ranging from 3000 to 12500, H/B 1 to 14 and dimensionless curvature values (R/L) of 0.5, 0.5125, 0.566, 0.725 and 1.3 of impinging surface. They performed simulations with the k-ε model for concave plate with dimensionless curvature value (R/L) = 0.725 and flat plate with enhanced wall functions. They observed a decreased value of the pressure coefficient at the stagnation point with H/B and variation of the local pressure coefficient computed with the standard k-ε modelwith an enhanced wall treatment was in excellent agreement with the experimental data.

Caggese et al. [5] investigated the heat transfer characteristics of fully confined jet impingement experimentally and numerically with low H/D values of 0.5 to 1.5 and Re in the range of 16500 to 41800. They observed significant effect of different separation distances on the flow field and hence it affected the distribution of heat transfer coefficient. Their numerical results showed satisfactory prediction of local and average Nusselt numbers.

O'Donovan and Murray [6] experimentally investigated flow field and heat transfer characteristics from a heated flat plate with H/B of 0.5 to 8 and Re from 10000 to 30000. They showed secondary peaks in heat transfer distributions in the radial direction for jet to plate spacing less than two diameters owing to a sudden growth in turbulence in the wall jet region. They also showed that high heat transfer regions are associated with the high fluid velocity and turbulence intensity regions. They observed peaks in heat transfer distribution at locations where the velocity fluctuations in normal direction to impingement plate were high.

O'Donovan and Murray [7] experimentally investigated the temporal nature of heat transfer and fluid flow with the values of all parameters being same as in their former study. They showed that the growth of vortices through the distance from the jet axis affected the heat transfer coefficient in the wall jet region.

Alekseenko et al. [8] experimentally studied the influence of swirl rate of an impinging jet on flow field using PIV and stereo PIV techniques. They considered H/D = 3, Re = 8900 and swirl rate from 0 - 1.0 and observed a decreased level of pressure diffusion with increasing swirl rates. They showed a large recirculation zone between the jet exit and the impinging surface at a swirl rate of 0.41 and vortex breakdown at swirl rates of 0.70 and 1.0 with a smaller recirculation. Strong generation of turbulence was observed due to vortex breakdown resulting in high values of TKE in the local regions.

Bakirci and Bilen [9] experimentally visualized the temperature distribution on the impingement surface maintained at a constant temperature for the multichannel, swirling and conventional jet impingements by means of liquid crystal technique. They used swirl generator insert with the swirl angle fixed at 00, 22.50, 410 and 500 to alter the direction and strength of the swirl. The local Nusselt numbers for the multi-channel impinging jet (at an angle of 00) were found much higher than those for other two configurations. The positions of the heat transfer peaks were moved sensitively from the stagnation point, when swirl angles were increased but decreased values of local and average Nusselt numbers were observed when swirl angles were increased.

Senter and Solliec [10] experimentally investigated flow field of a confined turbulent slot jet impinging orthogonally on a moving flat surface using PIV. They performed experiments for H/B = 8, Re = 5300, 8000 and 10600 and four surface to jet velocity ratios (0, 0.25, 0.5 and 1). They observed that the flow field topology was independent of Re ranging from 5300-10600 at a particular surface to jet velocity ratio.They observed a slightly affected flow field at a surface to jet velocity ratio of 0.25 and the most influenced flow field pattern was found at the surface to jet velocity ratio of unity. Turbulence intensity measurements in the vicinity of the stagnation zone showed enhanced values with increasing surface to jet velocity ratio.

Ozmen [11] experimentally analyzed flow characteristics of confined twin air jets impinging normally on a surface at high Re with the smoke wire technique. The uncertainties associated with axial velocity and turbulence velocity measurements in the vertical direction were +3% and +4%, respectively, and with pressure measurement it was +2%. He obtained pressure distribution on the impingement and confined surfaces with Re in the range of 30000 to 50000, H/D 0.5 to 4 and jet to jet spacing (L/D) 0.5 to 2. He observed sub-atmospheric region at the nozzle to plate spacing up to 1 diameter on impingement and confined plate both for the range of Re and jet to jet spacing studied and concluded that sub-atmospheric regions and heat transfer coefficients peaks were co-related for low spacing.

Al-Sanea S [12] numerically investigated the heat transfer and flow characteristics of an impinging laminar slot jet. He observed identical results for free and semi-confined jet impingements with a slight difference down the region due to entrainment effects. He also showed increased Nu with jet Re and Pr and it decreased with a reduction in the H/B value. They showed that the cross-flow effect can reduce the nominal Nu by as much as 60%.

Further Sharif and Banerjee [13] numerically investigated heat transfer from a moving plate due to confined slot jet impingement. They specified 2% turbulence intensity at the jet exit and a length scale equal to 2B with constant pressure outlet condition to handle such complex flow situations due to plate movement.

Arquis et al. [14] computationally studied the flow and heat transfer features for cooling of an array of multiple protruding heated blocks using laminar slot jet and studied the effect of channel height, Re, slot width, spacing between blocks and height of blocks on heat transfer and fluid flow. They categorized the flow field with the presence of impingement flow and wall jet flow with possible survival of a primary circulation cell between the jet and confinement wall. They observed secondary circulation cells between the blocks, plus a secondary recirculation cell at the top surface of the downstream blocks. The strength and size of primary and secondary circulation cells and the flow separation (formation of recirculation cells) at the top surface of downstream blocks were found to increase with Re, channel height and decreasing slot width. These flow structures significantly affected the heat transfer characteristics. They also observed that cooling efficiency of all the blocks increased with Re and through reduction in slot width and channel height. But an increase in Re and channel height and reduction in slot width decreased the heat transfer rates from the downstream blocks because of the formation of recirculation cells at the top surface of these blocks.

Dutta et al. [15] observed that the inflow turbulence intensity strongly affected the heat transfer distribution on the wall and the discretization scheme did not produce any significant difference in computed results for second or higher order scheme used.

Hattori and Nagano [16] carried out DNS and observed the effects of nozzle to plate spacing. They observed a secondary peak in the local Nu in the wall jet developing region for low H/B value and showed larger wall normal turbulence intensity close to the wall in the wall jet region and hence a secondary peak in Nu occurred. They also observed a secondary peak in the skin friction coefficient in case of low H/B value similar to that of local heat transfer.

Jaramillo et al. [17] performed DNS and RANS computations in order to assess the flow field and heat transfer characteristics of plane impinging jets with Re = 20000 and H/B = 4. They used DNS results reference data to assess the performance of several RANS based models. They considered periodic boundary condition in the span-wise direction and turbulent length scale of 0.015B at the inlet and suggested that the outflow should be placed at least at 40B to capture main recirculating flow from the jet centerline. They showed that DNS produced noteworthy outcome on the local heat transfer upon changing the boundary condition at theimpingement wall from a constant heat flux to a constant temperature.

Kubacki and Dick [18] simulated plane impinging jets using the k-ω based hybrid RANS/LES and k-ω RANS models with H/B = 10, 9.2 and 4 and Re from 13500 – 20000. They set πB as the size of the domain in the span-wise direction and applied periodic boundary and turbulent length scale at the inlet was set as 0.015B and observed that the hybrid models predicted the wall shear stress and heat transfer rate on the impingement plate in much better way than by the k-ω RANS model. They also observed that the hybrid model was capable of resolving the evolution of the large-scale structures originating at the jet exit and its destruction in to smaller scales. Further

Kubacki and Dick [19] simulated the flow and convective heat transfer characteristics of round impinging jets for different set of H/D of 2, 6 and 13.5 and Re of 5000, 23000 and 70000. They tested the k-ω model with three hybrid RANS/LES models and observed that the turbulence kinetic energy was overpredicted at low value of H/D computed by RANS model. For high H/D value the turbulence mixing was underpredicted by RANS model in the shear layer and thus length of the potential core became too large and therefore heat transfer results were also over-predicted. They observed that all hybrid RANS/LES models produced better result by improving over- and under-predictions of RANS model.

Kubacki et al. [20] studied the capability of hybrid RANS/LES computations of jet impingement with Detached Eddy Simulation (DES) and Partially-Averaged Naiver Stokes (PANS) model for two configurations, i.e., H/B = 10, Re = 13500 and H/B = 4, Re = 20000. They considered the outflow boundary condition at X = +40B, periodic boundary condition in the span-wise direction (width equal to π) and turbulent length scale as 0.1667B. For DES the turbulent length scale was substituted by the grid size in the eddy viscosity formulation and in the destruction term of equation and for PANS it was substituted from the sub-filter dissipation rate and total turbulence kinetic energy. They observed that the hybrid models in contrast to RANS models were capable of replicating the turbulent flow dynamics of the impinging jet in the shear layer. They observedthat the prediction of the skin friction was better with DES than with PANS.

III. CONCLUSION

A comprehensive review of jet impingement heat transfer including different physical and computational aspects of impinging flows is presented.The study has shown that several parameters affect the flow and heat transfer characteristics of jet impingement and these have found special attention in the literature experimentally and numerically. The studies also suggested that LES is capable of predicting the flow and heat transfer characteristics within the accepted accuracy limits while DNS can be applied to simple geometries with low values of Re.

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