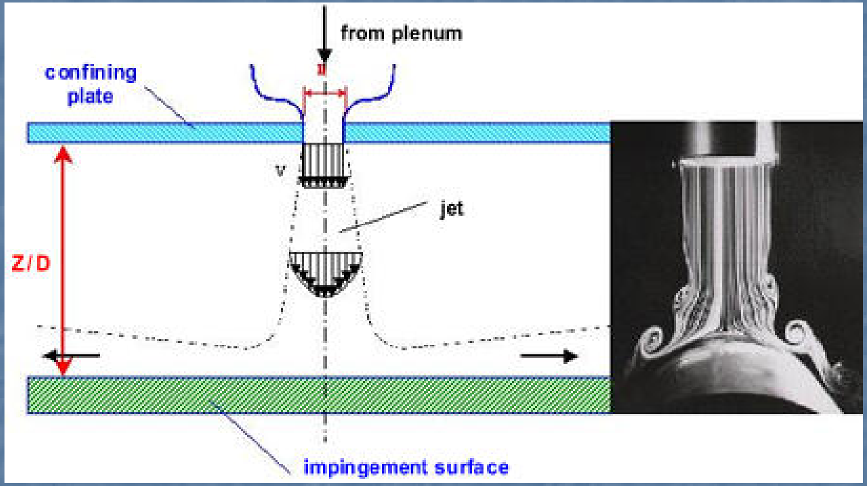
Free Surface Impinging Jet

Work done by: Mr. Poh Hee Joo

Reviewed by : Prof. Arun Mujumdar

Introduction - Physics



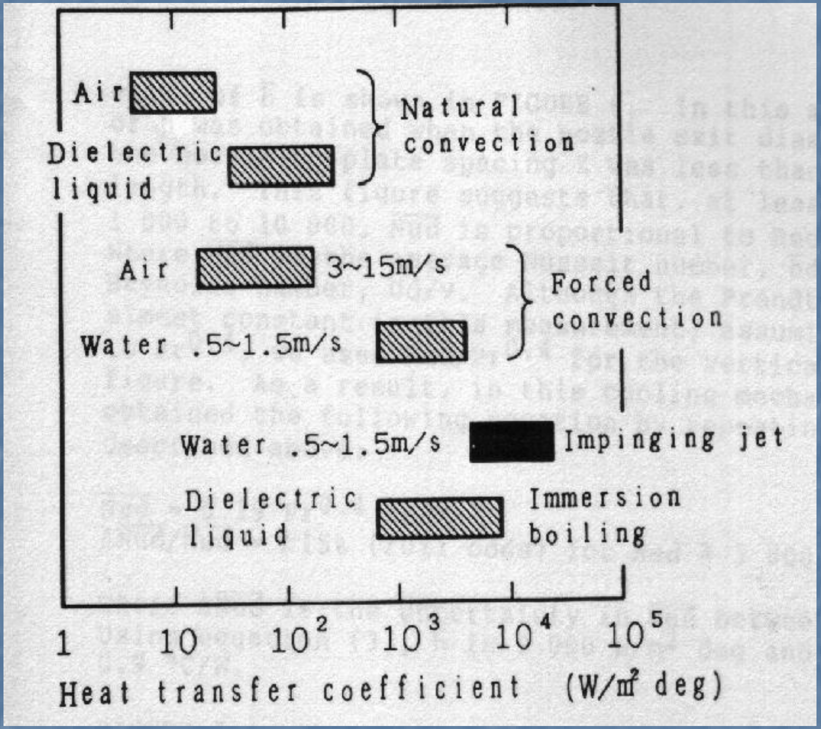
- Three characteristic region
- Free Jet Region
    - Potential Core
    - Shear Layer
- Impingement/Stagnation Region
- Wall Jet Region

- Thin hydrodynamic and thermal boundary layers within the stagnation (impinging) point help to remove a large amount of heat

Introduction - Application

- Vertical/Short Take-Off and Landing (V/STOL) aerodynamics
- Internal cooling of turbine blades
- Cooling of turbine blade, x-ray devices, laser weapons and fusion blankets, microelectronic components and neutron beam system
- Quenching and annealing of non-ferrous sheet metals and plastic sheets
- Tempering of glass and drying of textiles, wood, film materials and paper
- Freezing of tissues in cryosurgery

Introduction - Application



- Use of impinging water jets is one of the most effective means of heat transfer. (Yamamoto et al., 1987)

Literature Review - Free Surface Impinging Jet

- Fujimoto, Hatta & Viskanta (1999)
  - Numerical simulations of convective heat transfer to a radial free surface jet impinging on a hot solid - using RIPPLE commercial CFD code - A Computer Program for Incompressible Flows with Free Surface. LA 12007-MS, Los Alamas National Laboratory.
  - Turbulence neglected, no hydraulic jump

Mathematical Modelling - Free Surface Jet Impingement

- 2D - Axis symmetric - Include surface tension, viscosity and gravity, but turbulence is neglected

Continuity Equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\rho_f r v_r\right)+\frac{\partial}{\partial z}\left(\rho_f v_z\right)=0$$

Radial Momentum equation

$$\rho_f\left(v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{2}{3}\mu r\left(2\frac{\partial v_r}{\partial r}-\frac{v_r}{r}-\frac{\partial v_z}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v_r}{\partial z}+\frac{\partial v_z}{\partial r}\right)\right]$$

Axial Momentum equation

$$\rho_f\left(v_r\frac{\partial v_z}{\partial r}+v_z\frac{\partial v_z}{\partial z}\right)=-\rho_f g-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left[\mu r\left(\frac{\partial v_r}{\partial z}+\frac{\partial v_z}{\partial r}\right)\right]+\frac{\partial}{\partial z}\left[\frac{2}{3}\mu\left(2\frac{\partial v_z}{\partial z}-\frac{v_r}{r}-\frac{\partial v_r}{\partial r}\right)\right]$$

Mathematical Modelling - Free Surface Jet Impingement

- 2D - Axis symmetric - Include surface tension, viscosity and gravity, but turbulence is neglected

Energy Equation

$$\rho_f \left(v_r \frac{\partial \left(c_{p,f} T_f \right)}{\partial r} + v_z \frac{\partial \left(c_{p,f} T_f \right)}{\partial z} \right) = \left[\frac{1}{r} \frac{\partial}{\partial r} \left(k_f r \frac{\partial T_f}{\partial r} \right) + \frac{\partial}{\partial z} \left(k_f \frac{\partial T_f}{\partial z} \right) \right] + \left(v_z \frac{\partial p}{\partial z} + v_f \frac{\partial p}{\partial r} \right)$$

$$+ \mu_f \left\{ 2 \left[\left(\frac{\partial v_r}{\partial r} \right)^2 + \left(\frac{v_r}{r} \right)^2 + \left(\frac{\partial v_z}{\partial z} \right)^2 \right] + \left[\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right]^2 - \frac{2}{3} \left[\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} \right]^2 \right\}$$

FLUENT –Volume of Fluid (VOF) Model

- VOF (Volume of Fluid) method was pioneered by Hirt & Nicolas (1982)
- Tracing fluid regions through an Eulerian mesh of stationary cells

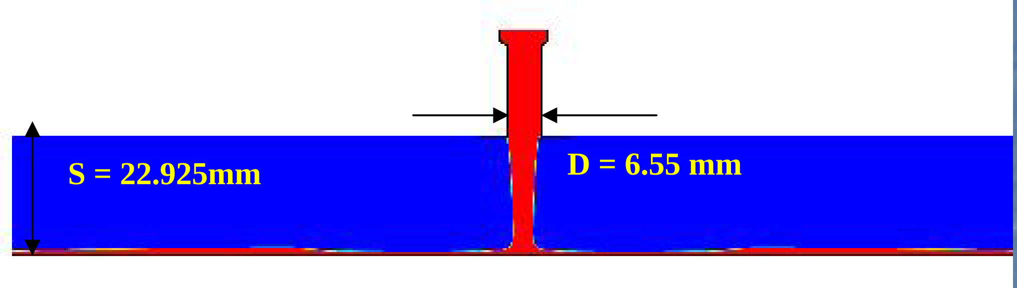
$$\frac{DF}{Dt}=\frac{\partial F\left(\vec{x},t\right)}{\partial t}+\vec{V}.\nabla F\left(\vec{x},t\right)=0$$

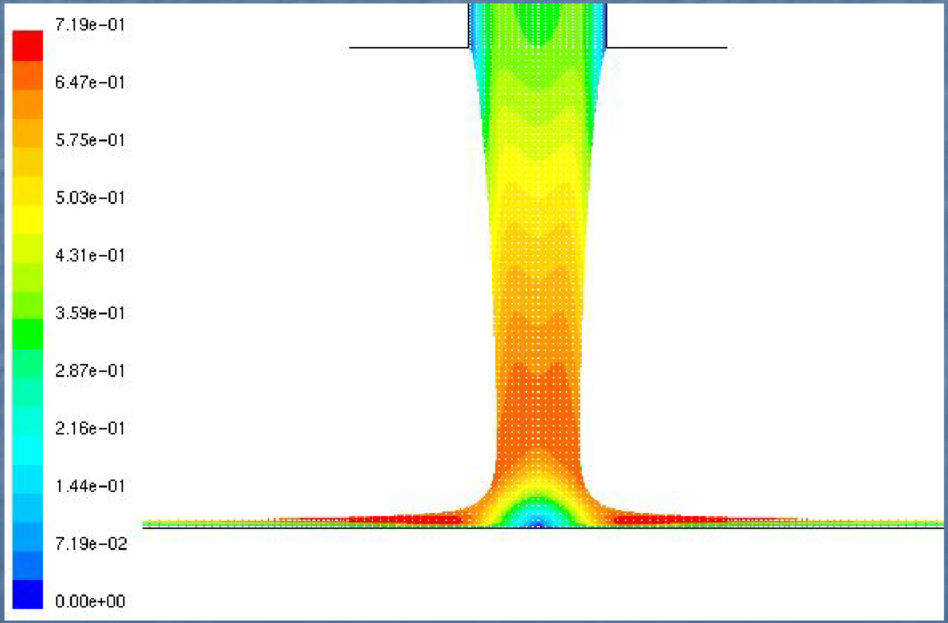
- *F* is defined as the volume fraction of fluid whose value is unity at any point occupied by fluid and zero elsewhere. A cell with F values between zero and one contain a free surface
- The surface tension model is the continuum surface force (CSF) model proposed by Brackhill *et al*. With this model, the addition of surface tension to the VOF calculation results in a source term in the momentum equation

$$p_s-p_A=\sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

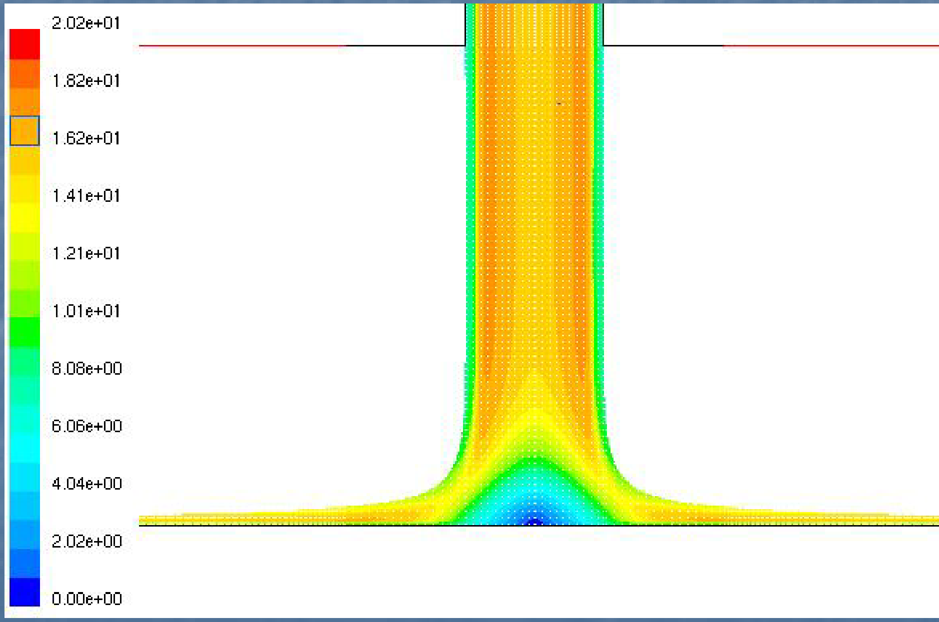
  - p_s and p_A are the surface and atmospheric pressure, respectively. R_1 and R_2 are the principal radii of curvature at a point on a free surface, respectively, and σ is the surface tension coefficient between air and water

Heat transfer under free surface impinging jet





Re = 1,000



Re = 10,000

Validation of laminar flow field in stagnation zone by comparison with experimental data

- For free surface impinging jet, Azumo and Hoshino (1984) reported a critical discharge Reynolds number, based on jet diameter, of 4.8 x 10^4. This could be attributed to the re-laminarization of flow over the impinging jet owing to strong favourable pressure gradient parallel to the impingement surface (Incropera, 2000)
- Leinhard (1995) had obtained theoretical expression for the viscous boundary layer thickness

$$\frac{\delta}{D_i} = \frac{1.95}{\sqrt{G_r \,\mathrm{Re}_{D_I}}}$$

$$G_r = \left.\frac{d\left(u_\infty / V_i\right)}{d\left(r / D_i\right)}\right|_{(r/D_i)=0}$$

Dimensionless radial free stream velocity gradient in the stagnation zone

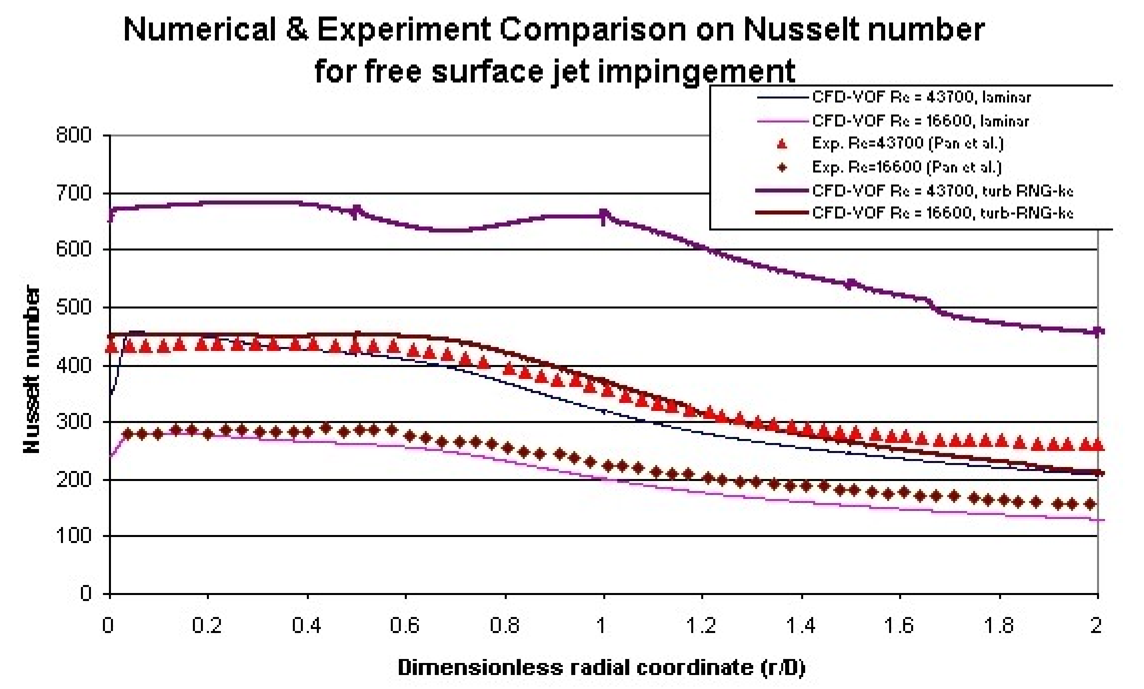
- For Re = 43,700, Gr = 0.916 (uniform velocity profile), d = 10.9mm, δ= 0.1062mm

Validation of laminar flow field in stagnation zone by comparison with experimental data

The following parameters were used in the CFD-VOF simulation

- A single nozzle to plate spacing of z/d = 1
- Nozzle exit diameter = 0.0109m
- Two Reynolds based on nozzle exit diameter of 16,600 & 43,700
- Three types of velocity profile at nozzle exit, namely uniform, parabolic & 1/7th power law
- Laminar and RNG k-e turbulence model
- Radial distance of 2.5D away from the stagnation zone

Heat transfer under free surface impinging jet – Nusselt Number

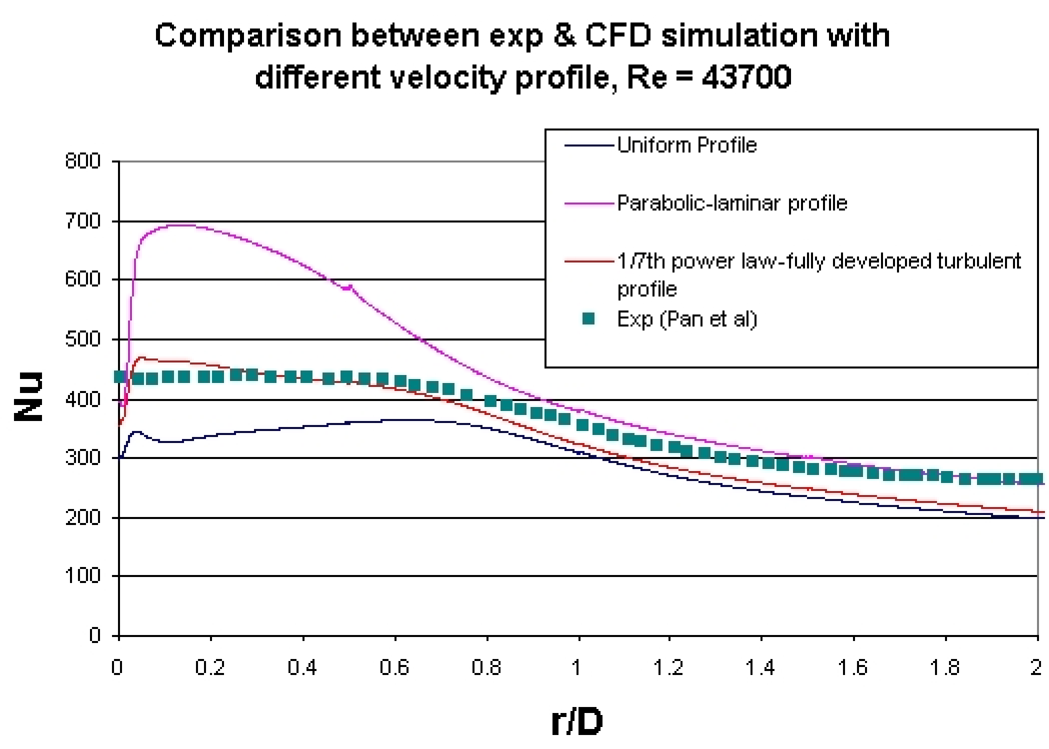


Correlation for stagnation heat transfer for turbulent jets issuing from fully developed pipe-type nozzles (Steven *et al*. (1992)

$$Nu_{d,o} = 0.93\,\mathrm{Re}_d^{1/2}\,\mathrm{Pr}^{0.4}$$

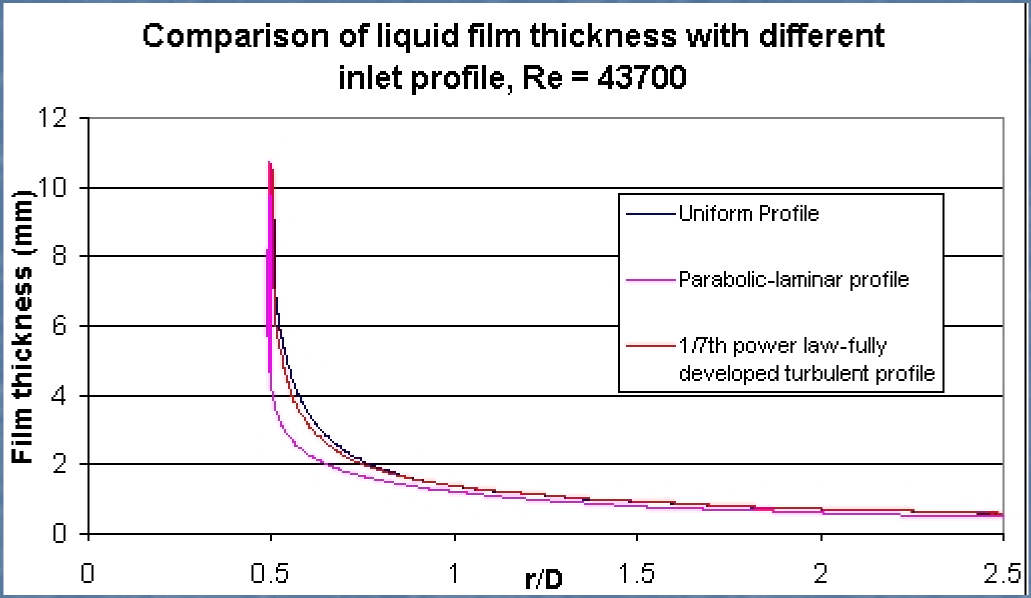
Laminar model in close agreement with exp. results, whereas turbulence model overestimate the exp. data by 150%. Relaminarization of flow in the stagnation region does occur.

Heat transfer under free surface impinging jet – Nusselt Number



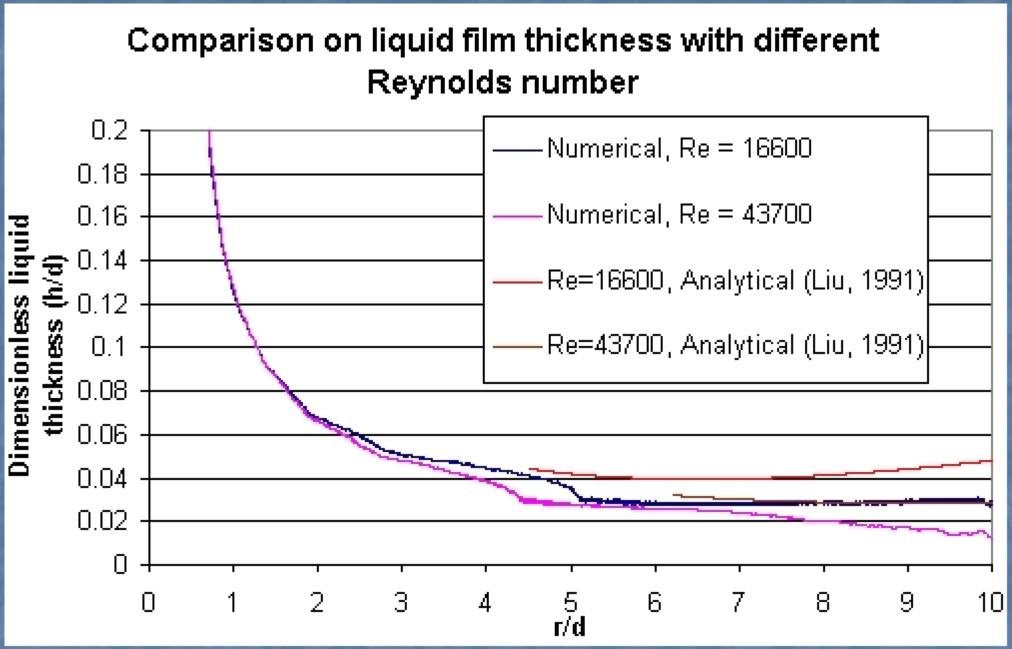
Laminar parabolic velocity profile gives the highest Nusselt number. Use converging nozzle to suppress turbulence generation within nozzle wall, in order to produce laminar parabolic profile and enhance heat transfer performance at the stagnation zone

Heat transfer under free surface impinging jet – Liquid Film Thickness



Parabolic profile could produce the thinnest liquid film. Largest velocity gradient across the nozzle cross-section, and increases the surface tension

Heat transfer under free surface impinging jet – Liquid Film Thickness



Liquid film thickness at viscous similarity region (Liu *et al*. (1991) and Leinhard (1995))

$$\frac{h(r)}{d} = \frac{0.1713}{\left(r/d\right)} + 5.147\,\frac{\left(r/d\right)^2}{\mathrm{Re}_d}$$

starting from

$$\frac{r_v}{d} \approx 0.177\,\mathrm{Re}_d^{1/3}$$

Thermal boundary layer can never reach the free surface as Prandtl number for water is 6.9. This number is greater than the critical Prandtl number value near five (5) as developed by Liu *et al*, and beyond this critical value and thermal boundary layer does not grow fast enough to reach the surface of liquid film.

Analytical value is always higher than the CFD simulation. Analytical expression solves only the radial momentum equation, but the numerical results are dealing with both the radial and axial momentum equation

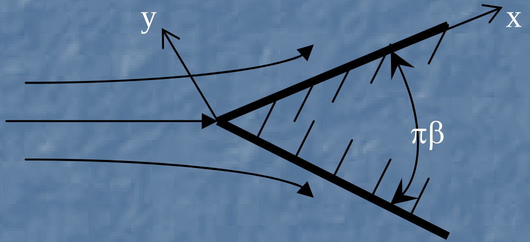
Heat transfer under free surface impinging jet – Falkner-Skan similarity solution

Detail about transformation from PDE to ODE of Falkner-Skan can be found from any Fluid Mechanics textbooks

$$F''' + \left[\frac{\varepsilon}{\nu}\frac{d}{dx}(U\xi)\right]FF'' + \left[\frac{\varepsilon^2}{\nu}\frac{dU}{dx}\right]\left\{1-(F')^2\right\} = 0$$

$$\frac{\varepsilon}{\nu}\frac{d}{dx}(U\varepsilon) = \alpha$$

$$\frac{\varepsilon^2}{\nu}\frac{dU}{dx} = \beta$$



The Falkner-Skan similarity solution with β= 1 underlines the laminar boundary layer flow and heat transfer in the stagnation region, which has been used to date.

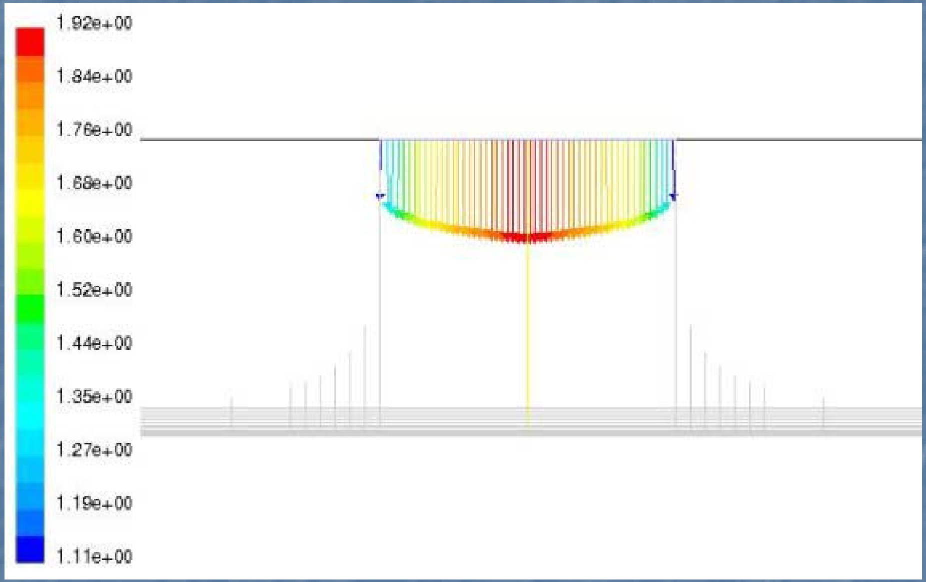
Using potential flow theory, Schlichting (1968) showed that the free stream velocity at the wedge surface varies with distance from the tip as

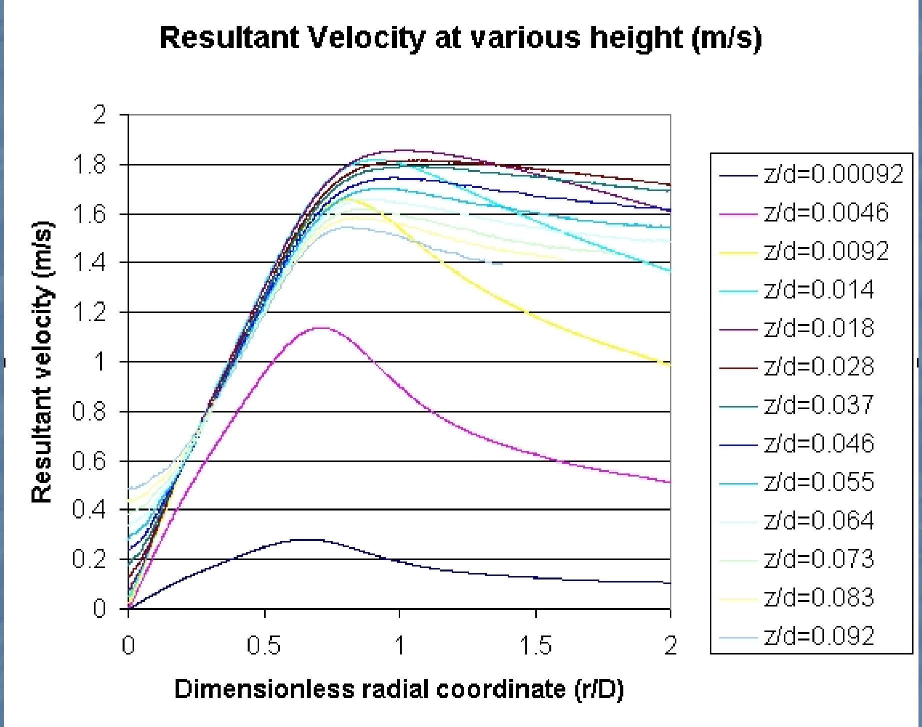
$$U = Cx^m$$

$$m = \frac{\beta}{2-\beta}$$

laminar impingement flow, β = 1, the free stream velocity varies linearly with distance from stagnation point

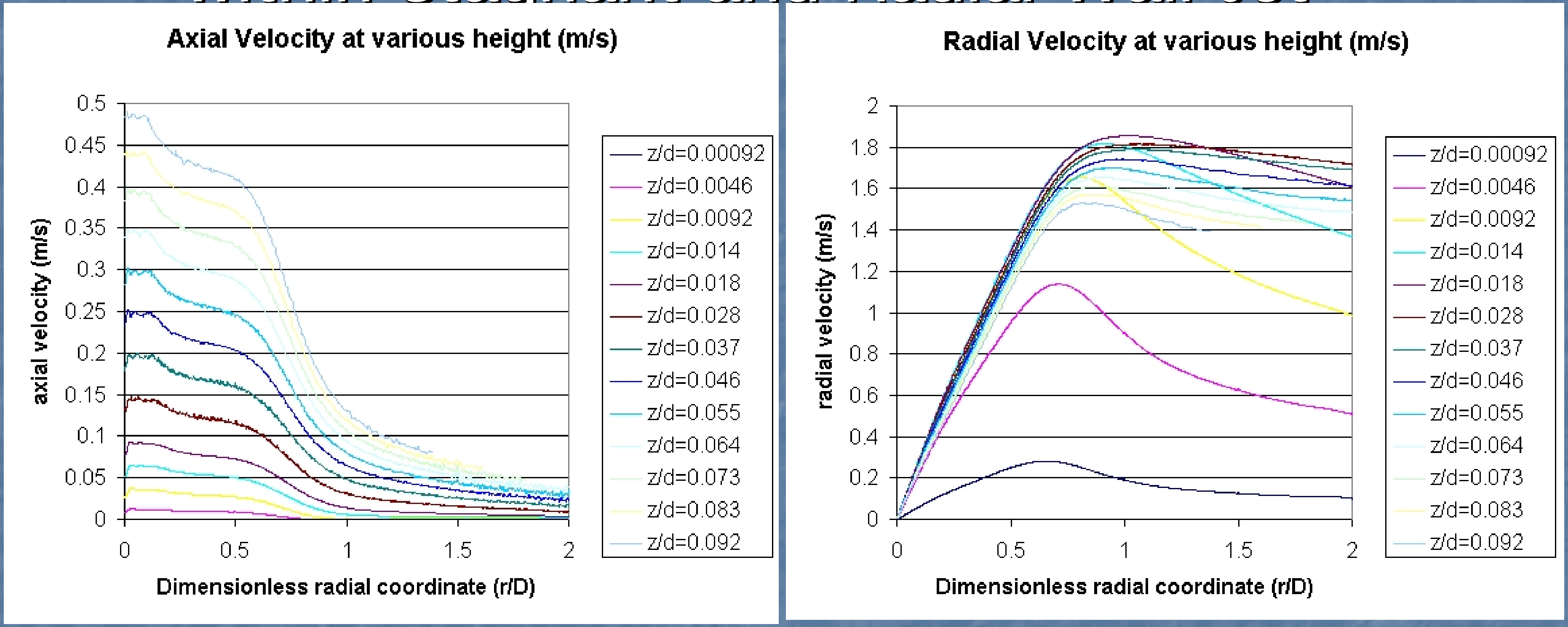
Heat transfer under free surface impinging jet – Radial & Axial Velocity within Stagnant and Radial Wall Jet





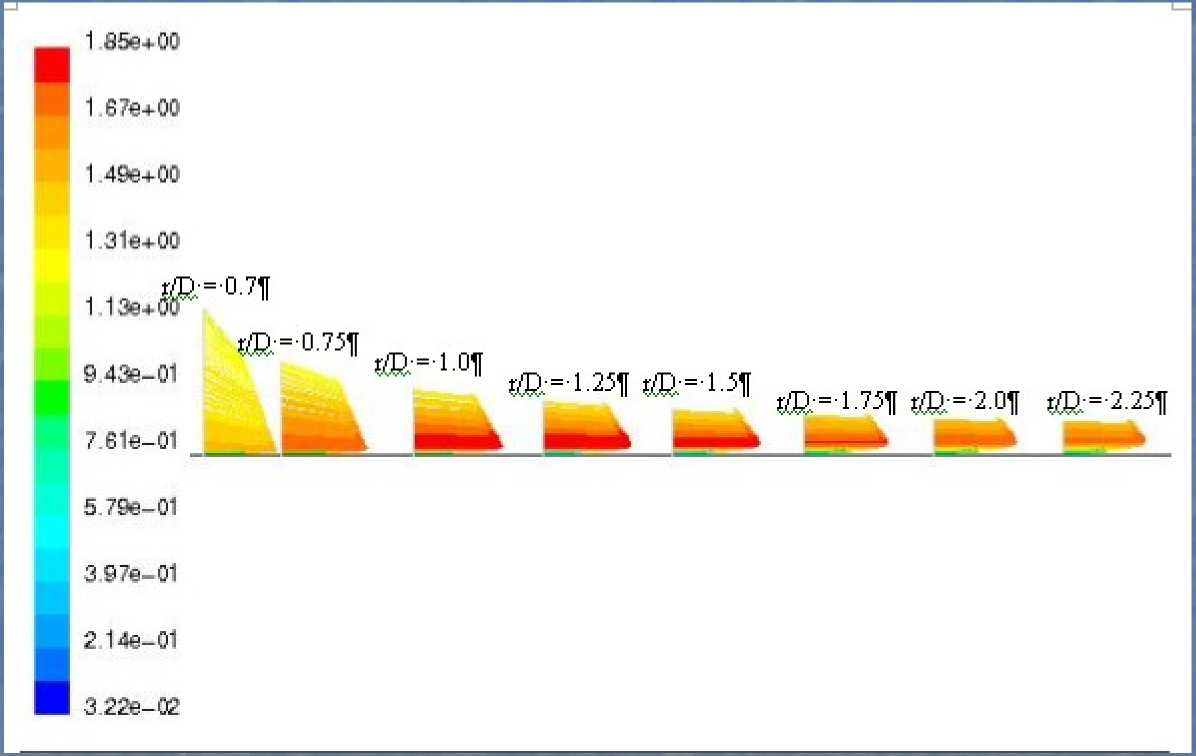
With the existence of pressure gradient, the free stream velocity is varies linearly with distance from where the flow originates (Schlichting (1968)) . In this case, the pressure gradient is attributed to the stagnation pressure created by impingement

Heat transfer under free surface impinging jet – Radial & Axial Velocity within Stagnant and Radial Wall Jet



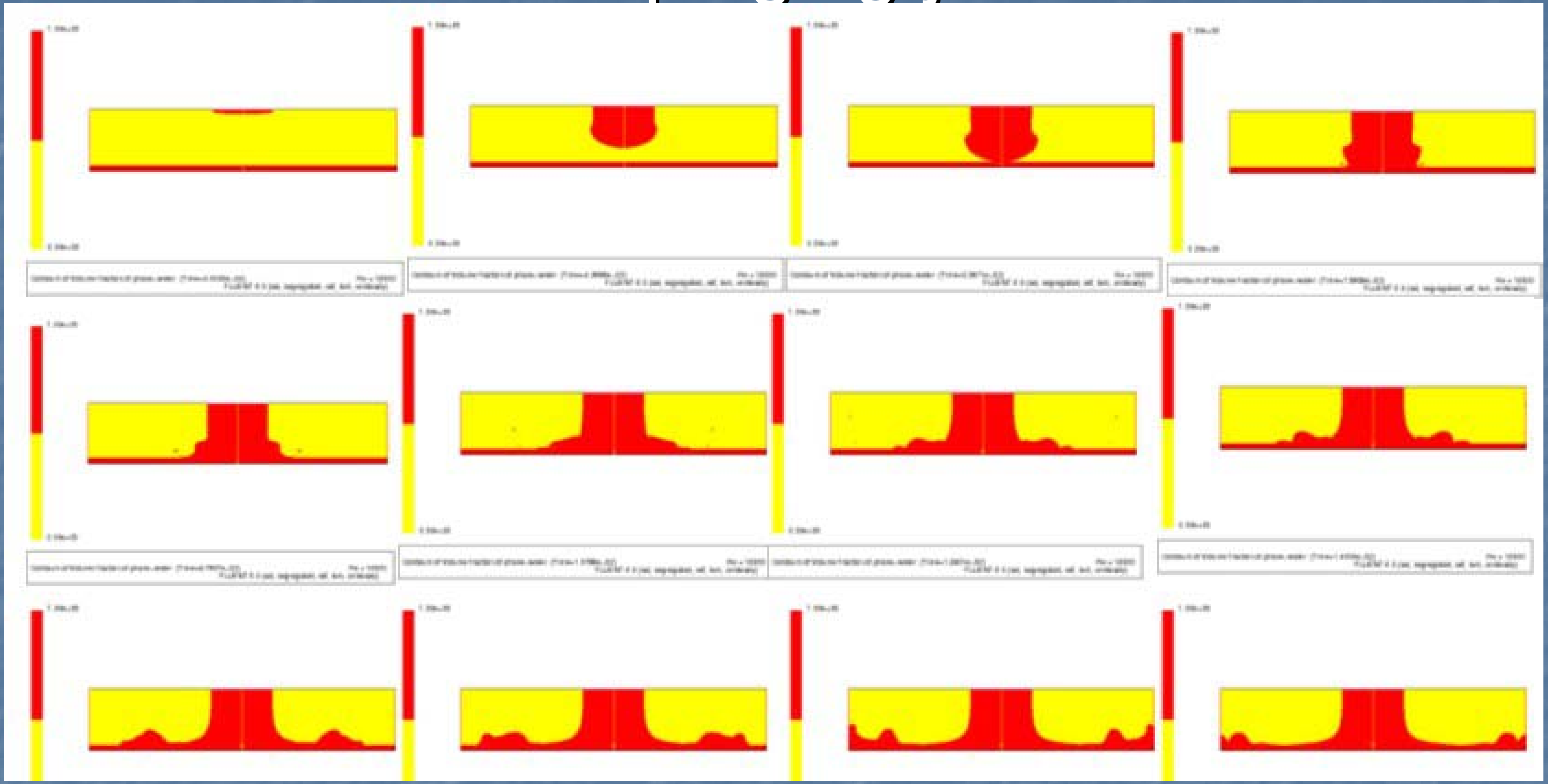
From z/d = 0.0092 upwards, the radial velocity increases linearly with the radial distance from the stagnation point until r/d ≈ 0.6, and the highest velocity gradient is observed at z/d = 0.018

Heat transfer under free surface impinging jet – Radial & Axial Velocity within Stagnant and Radial Wall Jet

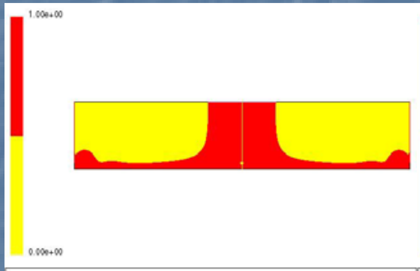


In 1964, Watson made the assumption that maximum velocity was at the free surface velocity, which travels at the jet exit velocity until viscous boundary layer reaches the free surface. However, Fig. 5.8 reveals that maximum velocity occurs internal to the liquid layer, rather than at the free surface location

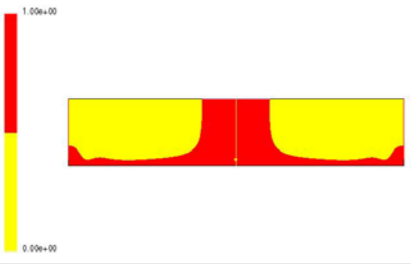
Heat transfer under partial submerge impinging jet



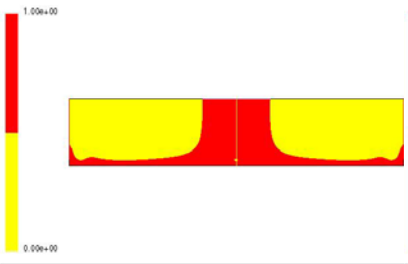
Heat transfer under partial submerge impinging jet



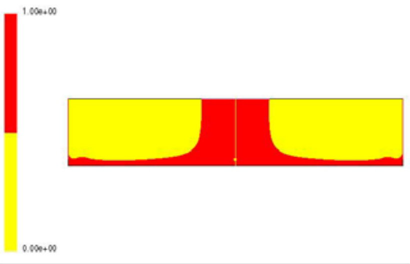
Contours of Volume fraction of phase-water (Time=4.5030e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



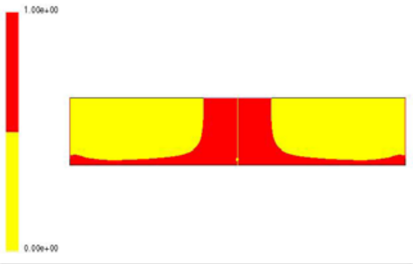
Contours of Volume fraction of phase-water (Time=5.0059e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



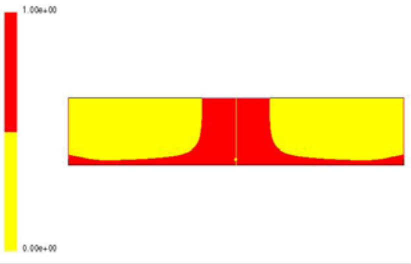
Contours of Volume fraction of phase-water (Time=5.5088e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



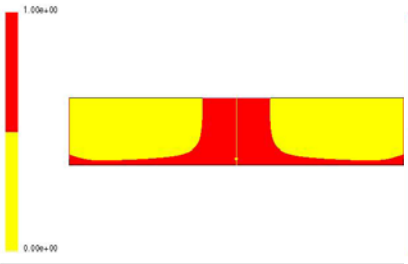
Contours of Volume fraction of phase-water (Time=6.0117e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



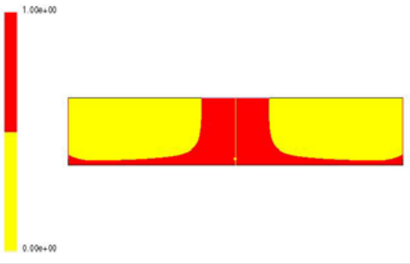
Contours of Volume fraction of phase-water (Time=6.5146e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



Contours of Volume fraction of phase-water (Time=7.0176e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



Contours of Volume fraction of phase-water (Time=8.0234e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)



Contours of Volume fraction of phase-water (Time=9.0292e-02) Re = 16600
FLUENT 6.0 (axi, segregated, vof, lam, unsteady)

Heat transfer under partial submerge impinging jet

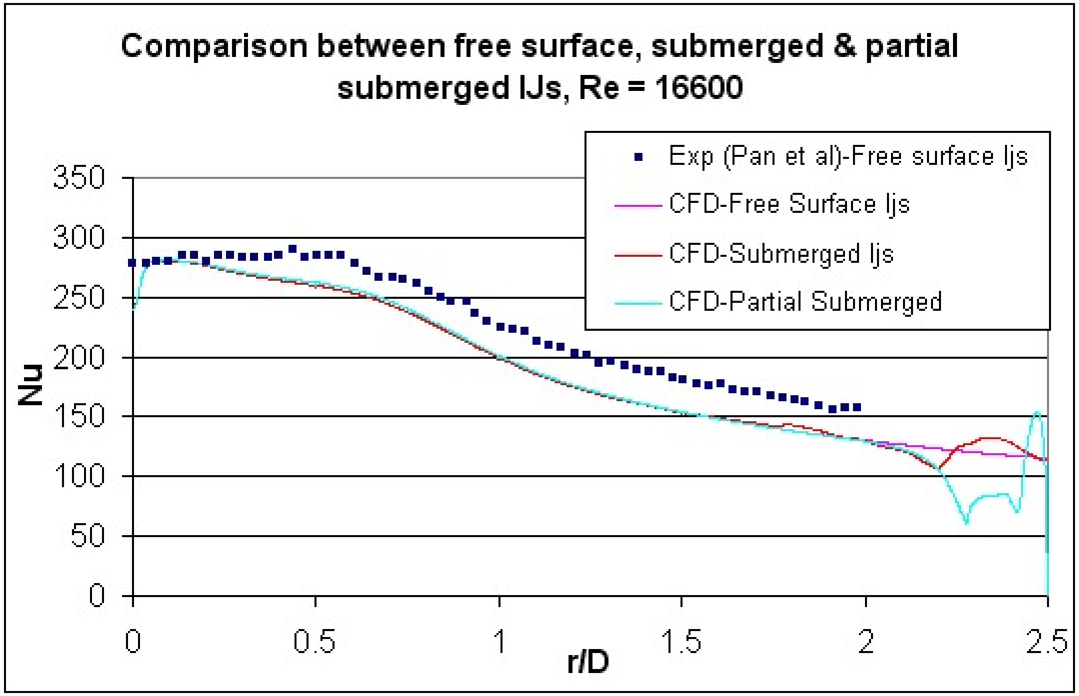


Figure 5.15: Nusselt number comparison for three different scenario of impinging jet

Marginal increase on the convective heat transfer performance for partially submerged jet

Conclusions

- For free surface impinging jet, even at Reynolds number (based on nozzle exit diameter) as high as 43700, the flow field at the stagnation zone is predominant laminar as the strong favourable pressure gradient acts to laminarize the flow in the stagnation zone. The numerical simulation results, when compared to the experimental data from literature (Pan et al, 1993), further verify the phenomena. When the turbulence model (RNG κ-ε, with two-layer zone wall roughness effect) is used to solve the mathematical equation, the Nusselt number tend to overestimate the experimental data by 150%, whereas the laminar model predict reasonable data when comparing to experimental data, differ by only 15%

Conclusions

- It was found that the laminar parabolic velocity profile gives the highest Nusselt number. Hence, once should use the nozzle exit condition that would produce the parabolic velocity profile in order to achieve better heat transfer performance

- The unsteady-state simulation of a free surface liquid layer penetrates a stagnant liquid layer of depth 1mm in order to reach the thermally active impingement surface has been carried out. The whole process only takes less than 0.2s to reach steady state. The air bubble is entrained and trapped when liquid jet hitting stagnant liquid layer. The air bubble has potential risk to deteriorate heat transfer performance.

Conclusions

- Analytically, the stagnation region of axisymmetric jets is solved as a special case of the Falkner-Skan similarity analysis. It is dropping the y-momentum term in Navier-Stokes equation, and converting the x-momentum term from the parabolic PDE to become ODE. However, in the jet impingement flow, as the flow approach the stagnation zone, it will be decelerated in axial direction and accelerated in radial direction simultaneously. The region of changing flow direction, especially near the nozzle edge, the flow direction is not pre-dominantly in radial direction. Hence, the complete mathematical analysis should not neglect the y-momentum equation. As can be shown from the CFD Volume of Fluid numerical simulation, at the region about $r/D \approx 0.5$ and $z/D > 0.04$, the local axial velocity relative to resultant velocity is greater than 0.1. This imply that the axial velocity component (y momentum equation) cannot be neglected

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