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Logarithmic Behaviour of the Wall Layer for an Impinging Jet

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Abstract. *The law of the wall for a turbulent jet impinging orthogonally onto a flat plate is studied through the hot-wire anemometry. The main purpose here was to investigate any possible dependence of the defining parameters onto the local flow conditions. The work presents new measurements of mean velocity that will result in a new expression for the behaviour of the level of the law of the wall, parameter, A. The experiments were conducted for three nozzle-to-plate spacing and Reynolds number of 35,000.*

Keywords. *Turbulence, jet, impingement, scaling laws, Nusselt number.*

1. Introduction

The turbulent jet impinging onto a wall has been extensively studied by the present authors in three other recent publications (Guerra e Silva Freire (2003, 2004a, 2004b)). However, in all of those publications, our concern was dedicated to both the velocity and the temperature fields. In fact, when the present research started four years ago, the behaviour of the Nusselt number for different aspect ratios – the ratio between jet height and nozzle diameter – was our main interest. However, very soon it became clear to the present authors that an odd behaviour could be observed for the law of the wall.

This fact was not a particular new information. For the simpler case of a wall jet, some authors had previously reported that some kind of law of the wall could be identified from mean velocity profiles measured with small Pitot tubes or hot-wires (see e.g., Patel (1962), Tailland and Mathieu (1967), Ozarapoglu (1973), Irwin (1973)). These same authors, unfortunately, could not agree on a same formulation for the flow description. Their reported values for the log-law parameters varied in a large interval.

At this point, we must call the reader’s attention to the relevance of a thorough study on the existence of the law of the wall for wall jets. Indeed, Wygnanski et al. (1992) showed in a very detailed research that the most reliable method for measuring the wall stress is to use the slope of the mean velocity profile near the surface. This method was tested against floating drag balances, Preston tubes and the momentum integral equation.

Having said that, it is no surprise that the previous publications of the present authors on this subject have concentrated on a description of the inner layers of the flow. The previous works specifically analyzed the existence of the so called universal law of the wall for both the velocity and the temperature fields. Here, we will deal only with the velocity field. A recent host of experimental batteries has disclosed a much defined trend for the behaviour of the linear coefficient in the law of the wall that will be reported here for the first time.

The scaling procedure that was used was based on the stream-wise evolution of the flow represented by its maximum velocity. Özdemir and Whitelaw (1992)) had observed that, for an oblique impinging jet, a distinct logarithmic region could be identified that could be correlated through a scaling procedure based on the stream-wise evolution of the flow by the maximum jet velocity. This result was shown to be valid for both the velocity and the temperature fields. In fact, Narasimha et al. (1973) were the first to acknowledge that the traditional use of the nozzle diameter as the reference scaling for wall jet flows was not appropriate. They proposed that any reasonable scaling length should take into consideration the flow evolution.

This work, as mentioned before, will shown through some new results how the scaling laws governing the motion of a jet impinging orthogonally onto a surface can be correctly written.

Other authors have specifically studied the role of the scaling laws in wall jet flows. For example, Wygnanski et al. (1992) studied the relevance of the wall to the evolution of the large coherent structures in the flow.

In fact, a question that has been the object of many investigations is the behavior of the velocity field at the stagnation point. For cases where the Reynolds number is low enough so that the flow can be rendered laminar, asymptotic methods can be used to find analytical solutions in all flow regions except near the stagnation point, which presents a strong singularity. Consequently, even for this simple flow condition, calculation of flow pattern at the stagnation point is very difficult. The result is that a severe lack of information on the flow behaviour in the stagnation region exists. The reason for this is clear, due to the small scales that define this region, the placement of dedicated instrumentation is always very difficult.

The flow structure of an impinging jet produced by a nozzle can be highly complex due to the ambient fluid entrainment, flow separation, interaction of the flow with the impingement or confining walls, and generation of vortices. In this work, we will provide experimental data on turbulent semi-confined and unconfined impinging jets. Results are presented for the turbulent characteristics of a round jet.

Despite the critics of many researchers, the use of wall functions to by-pass the difficulties involved with the modeling of low Reynolds number turbulence is still an attractive means to solve problems in a simple way. Cruz and Silva Freire (1998) have proposed an alternative approach where new wall functions are used to describe the velocity and temperature fields in the wall logarithmic region. As the stagnation point is approached, these functions reduce to power-law solutions recovering Stratford's solution. The paper of Cruz and Silva Freire resorted to Kaplun limits for an asymptotic representation of the velocity and temperature fields. Results were presented for the asymptotic structure of the flow and for the skin-friction coefficient and Stanton number at the wall.

2. Short literature review

Before we present our results, let us make a short literature review in order to set the subject for the reader.

For the wall jet, the first studies were severally limited by the lack of any sophisticated instrumentation. As a result, the first experiments were limited to measurements of mean velocities in the vicinity of the nozzle, see e.g. Forthman (1934). Sigalla (1958) was the first to try to evaluate the skin-friction and also the first to measure the mean velocity at large distances from the nozzle. The development of the hot-wire anemometer in the sixties made it possible the development of much more detailed investigations.

Tailland and Mathieu (1967) noticed that the rate of spread of a wall jet and the decay of its maximum velocity were dependent on the Reynolds number, a feature that is not observed in a free jet. That raised questions on the reason for such difference.

The scaling laws for wall jets were particularly studied by Patel (1962), Ozarapoglu (1973) and Irwin (1973).

In the early nineties Özdemir and Whitelaw (1992) studied the problem emphasizing the large-scale transport of temperature by spatially coherent structures. These authors showed that an oblique impingement introduced vertical velocities that rendered the boundary layer equation inapplicable and resulted in a flow structure with strong azimuthally dependence. The large structures improved the transport of temperature but led to an inactive zone near the vortex center.

Cooper et al. (1993) and Craft et al. (1993) in two companion papers studied turbulent jets impinging orthogonally onto a plane surface. Cooper et al. reported an extensive set of measurements on the flow field; data for the mean velocity profile in the vicinity of the plate surface and also for the three Reynolds stress components lying in the *x-r* plane were presented. These data were used by Craft et al. to examine the performance of four different turbulence models: the κ–ε model and three-second order moment closures. The predictions obtained through the κ–ε model and one second order moment closure result in far too high turbulence levels near the stagnation point. As such, they also result in too high heat transfer coefficients. Adaptations on the other two models lead too much better predictions. None of the models, however, could successfully predict the Reynolds number effects on the flow. The authors concluded that this ought to be due to the two-equation eddy viscosity model that was adopted for all cases to span the near wall sublayer.

Numerical simulation of impinging jets using the κ–ε model was also performed by Knowles (1998). The author concluded that the Rodi and Malin corrections could not predict wall jet growth.

Dianat et al. (1996) have used the κ–ε model and one modified second-moment closure to make velocity field predictions in the stagnation as well as in the jet region. The second-moment closure was modified to account for the influence of the wall in distorting the fluctuating pressure field away from it. With this modification, the damping of normal velocity fluctuations was well predicted.

Nishimo et al. (1996) report the turbulence statistics in the stagnation region of an axisymmetric jet impinging vertically on a wall. They used particle-tracking velocimetry do measure the flow near the stagnation point and found that the turbulent normal stress of the axial component gave a substantial contribution to the increase in the static pressure near the wall. Turbulence was studied through an invariant map of the turbulent stress anisotropy. In the stagnation region, turbulence was close to an axisymmetric state.

The standard κ–ε model together with the logarithmic law of the wall was applied by Ashforth-Frost and Jambunathan (1996) to a semi-confined impinging jet; the nozzle-to-wall distance was two nozzle diameters and the Reynolds number 20,000. Laser-Doppler anemometry and liquid crystal thermography were used to determine velocity, turbulence and heat transfer data. In the developing wall jet, authors showed numerical heat transfer results to compare to within 20% of experimental data. However, at the stagnation point, heat transfer is over predicted by about 300%. The authors attributed this discrepancy to failure of the wall function to confirm to the physics of the flow.

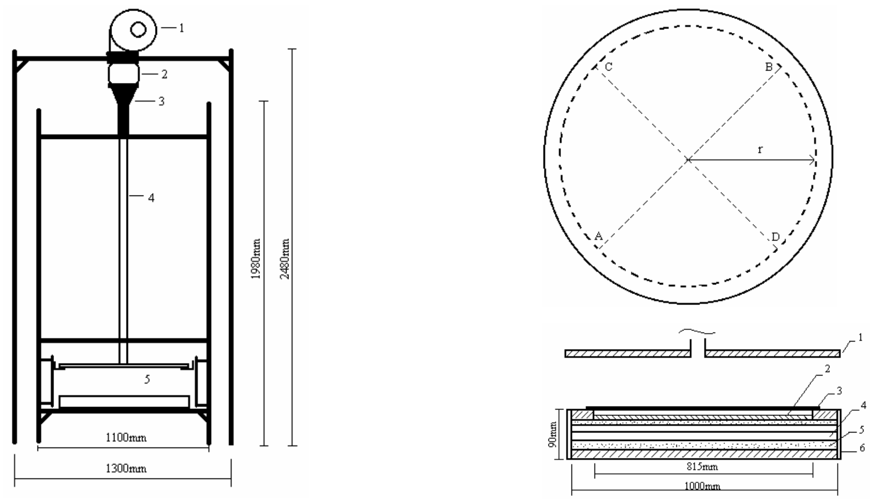
Knowles and Myszko (1998) carried out turbulence measurements in a jet impinging on a flat wall. Different nozzle-to-wall gaps were investigated. Measurements were conducted using hot-wire anemometry. Nozzle height was found to have a large effect on turbulence peak level for distances up to r/d = 4.5; lower nozzle-to-wall ratios caused an increase in peak level measured in all turbulent stresses in the stagnation region.

Confined impinging jets at low Reynolds number were experimentally studied by Baydar (1999) for a single and a double jet. The author concludes that a sub-atmospheric region occurs on the impingement wall at nozzle-to-wall gaps up to two and that there is a linkage between the sub-atmospheric region and the peak in the heat transfer coefficients.

3. Experimental methods

This section describes the experimental apparatus that was used for the investigations.

A schematic diagram of the apparatus and the problem geometry is illustrated in Fig. (1) below. Air at 22 ^{o}C was pumped through a centrifugal blower and passed through a 1350 mm long pipe with 43 mm internal diameter. Inside the pipe, a flow-straightener honeycomb was fitted constructed from drinking straws glued together; screens were also set in place. The jet was set to emerge from the circular nozzle with a bulk velocity of 12 m/s.

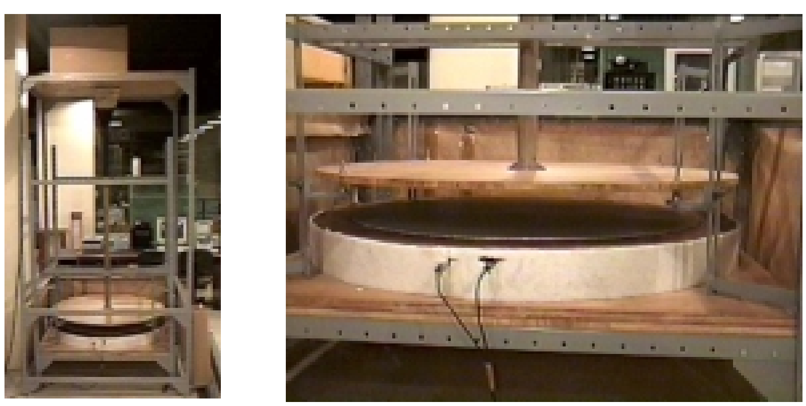


(a) (b)

Figure 2: Schematic diagram of (a) the experimental apparatus: (1) centrifugal blower, (2) flexible section, (3) contraction, (4) pipe, and (5) test section; and (b) test section and its heating system: (1) confinement plate, (2) electrical resistance, (3) impingement plate, (4), (5) and (6) thermal isolation.

The impingement flat plate was made of a 3 mm thick aluminum circular sheet. This sheet had 840 mm in diameter as shown in Figure 1. Photos of the experimental apparatus are shown in Figure 2.

The controlled parameters in the experiments were the nozzle-to-plate spacing, stagnation pressure. At each test, the centerline of the jet was lined up with the center of the impingement surface.



(a) (b)

Figure 2: (a) Experimental apparatus and (b) impingement plate.

The jet exit velocity was measured using a Pitot tube and an electronic manometer. Temperature profiles were measured using a chromel-constantan micro-thermocouple that was positioned using a traverse gear system with a sensitivity of 0.02 mm.

To perform the experiments, an elaborate procedure was devised. First, the flat plate was fitted with 27 pressure taps arranged at a cross formation. The readings of the pressure at these points were subsequently used to find the geometrical center of the jet; only when the pressure distribution was found to be completely symmetric the jet centerline was considered determined.

4. Results

The work will present complete results for three different geometries defined by the aspect ratio *H/D* = 1.0, 1.5 and 2.0. In previous publications by the present authors, just a fraction of these results had been presented. Also we will present a much detailed data presentation for the geometry given by *H/D = 2.0*.

The radial pressure distributions on the impingement surface were measured for the three nozzle-to-plate spaces of *H/D* = 1.0, 1.5 and 2.0, these are shown in Fig. 3. The plot shows that the pressure coefficient depends on the nozzle-to-plate spacing. The pressure measurements were non-dimensionalized with the dynamic pressure, $\rho U^2/2$, where ρ is the density of air and *U* is the jet exit velocity.

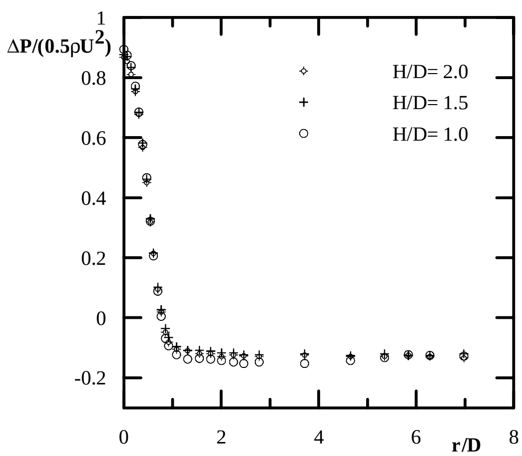


Figure 3: Radial pressure distributions of the jet.

The velocity and turbulent intensity profiles are shown in Figures 4 and 5.

The study of Özdemir and Whitelaw (1992) has shown that a Weibull distribution can be used to represent some of the global features of the profile, such as the position of the maximum and outer inflection points, but is not an adequate approximation for the near wall region. For this region, they showed that a semi-log relation can be used to model the inner equilibrium layer. Thus, it follows that

$$\frac{u}{u_\tau} = \frac{1}{\kappa}\ln\left(\frac{y u_\tau}{\nu}\right) + A \tag{1}$$

where u_τ is the friction velocity and κ is the von Karman constant.

The main contribution of Özdemir and Whitelaw (1992) was to show that, for the impinging jet, the inner layer appears to constitute a considerable part of the inner boundary layer and that if the outer edge of the equilibrium layer is attached to the point of maximum radial velocity, which is very close to the wall, then, this maximum, u_M, should be the appropriate velocity scale. The conclusion, therefore, was that parameter *A* is not invariant but changes with a deviation function. To describe *A*, these authors proposed a simple relation of the form $\boldsymbol{A = 1.292\ (u_M / u_\tau) - 6.2}$, where u_M denotes the point of maximum radial velocity.

To find the values of *A*, the graphical method of Coles (1956) was used. Here,we must point out that the thickness of the inner turbulent region for an impinging jet is very thin. That unique flow feature makes the fitting of a straight line to the logarithmic region a very difficult affair. The analysis of Wygnanski et al. (1992), however, can be invoked so that von Karman's parameter can be considered constant and that *A* varies from 5.5 to 9.5.

A data reduction from Figures 4 furnishes Figure 6.

This figure indicates that *A* increase with the maximum jet velocity. Please note that Figure 6 was constructed with the linear coefficients taken from the analysis of more than 90 velocity profiles.

Thus, the trends observed by Özdemir and Whitelaw (1992) have been repeated here. Furthermore, the analysis, carried out separately for each condition of nozzle-to-plate space, gave us a strong hint that a possible linear behaviour of *A* as a function of the maximum jet velocity exists.

Furthermore, this behaviour can be described by

$$A = 1.1 \frac{u_M}{u_\tau} - 27 \tag{2}$$

Compare this expression with the expression of Özdemir and Whitelaw (1992).

Despite our brief account of the problem of an orthogonal jet impinging on a wall, the following findings are unmistakable: 1) the variations of *A* for all three flow configurations is marked, 2) the level in the logarithmic expressions for the laws of the wall have a tendency to increased with increasing maximum jet velocity and wall temperature.

Thus, it appears that the trends observed by Özdemir and Whitelaw (1992) for the behaviour of the velocity law of the wall is also followed by the temperature law of the wall.

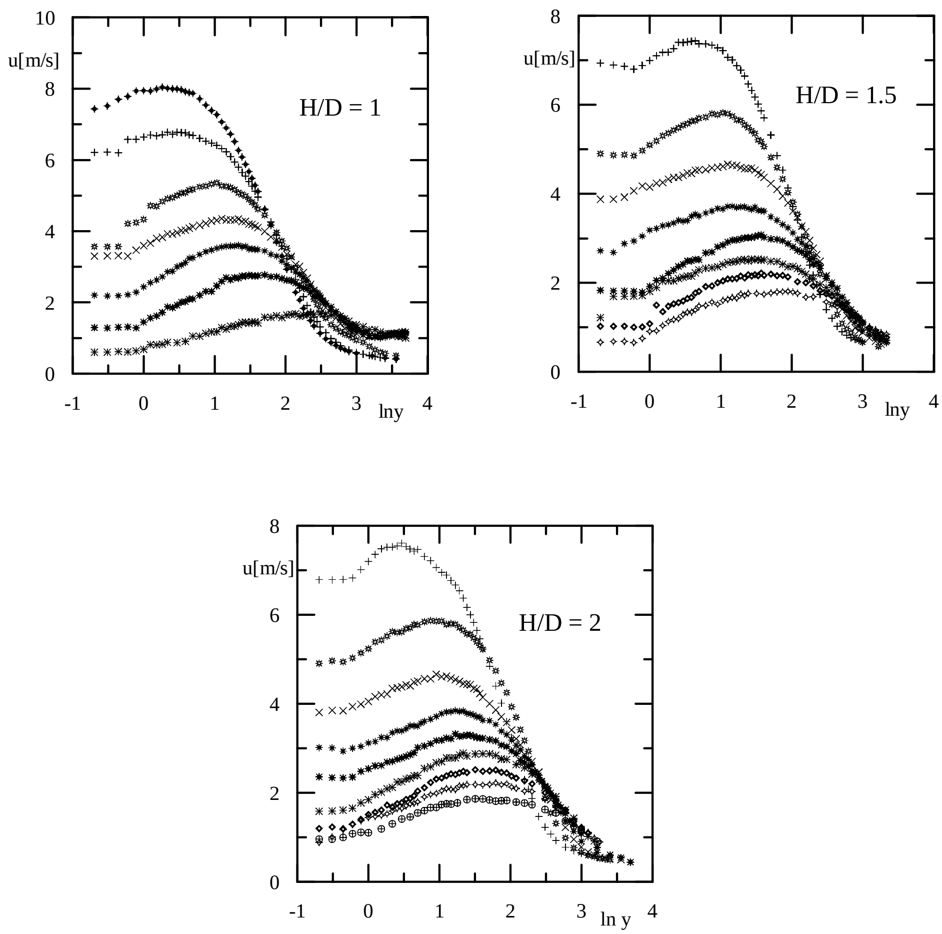


Figure 4: Mean velocity profiles in dimensional variables. Y is given in millimeters.

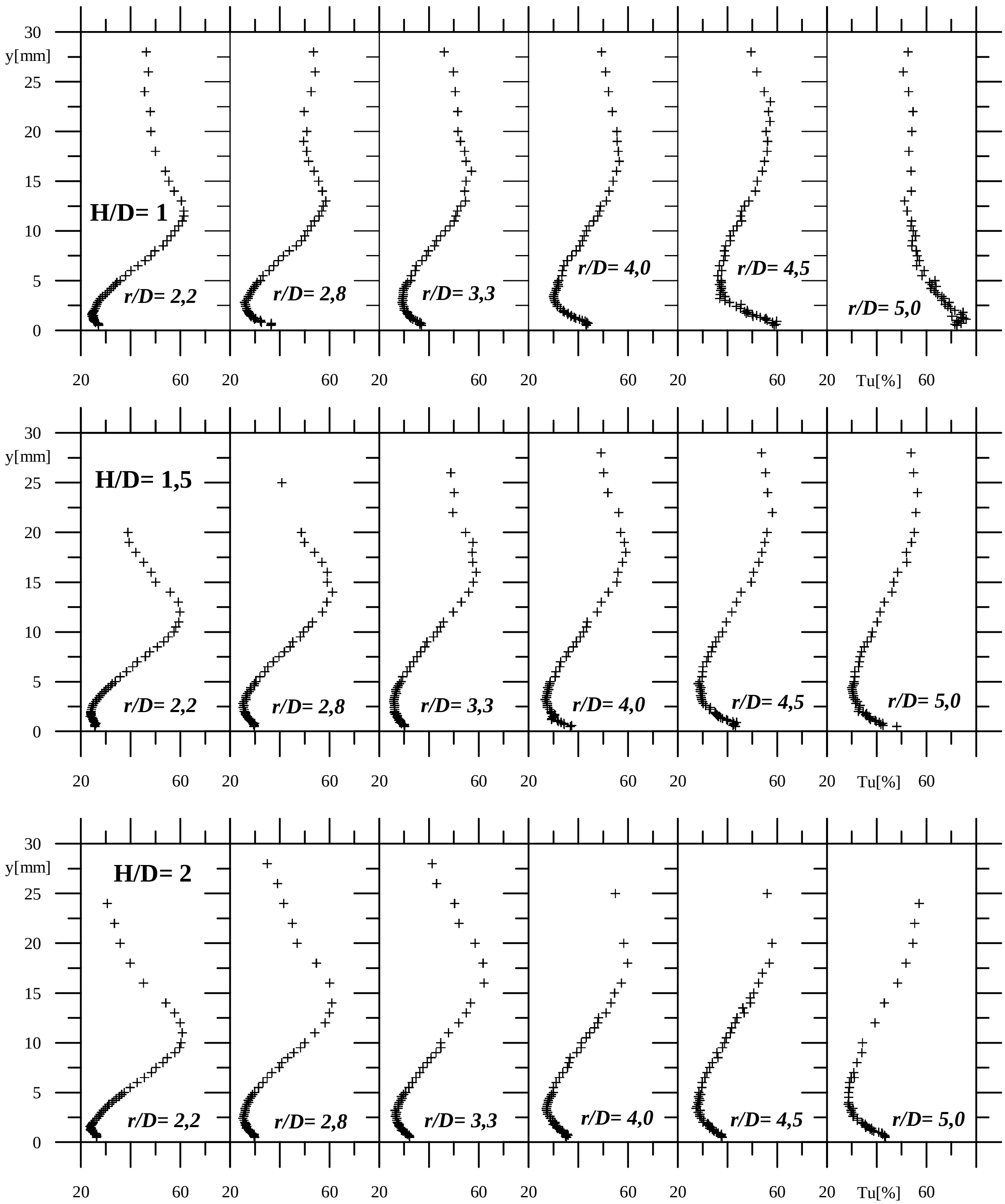


Figure 5: Longitudinal turbulent intensity profiles.

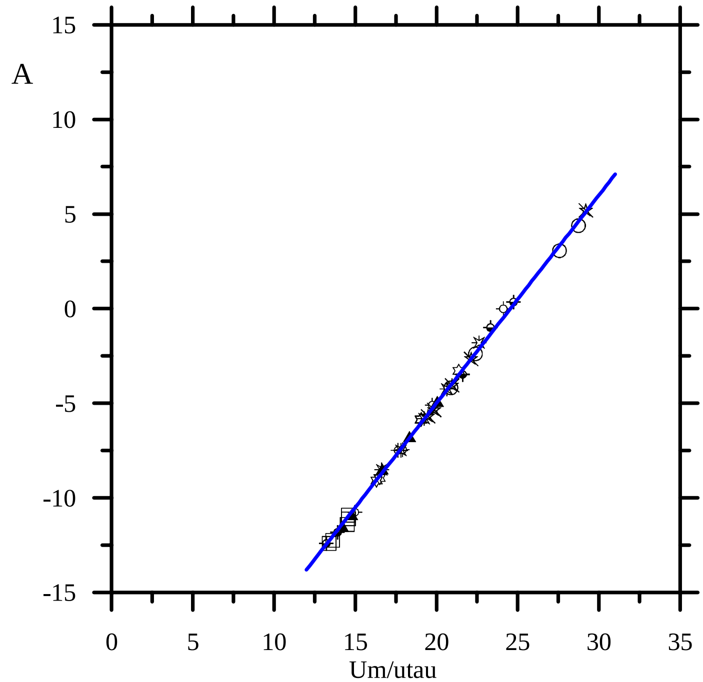


Figure 6: Deviation function for the velocity profiles.

5. Conclusion

The present work has described the behavior of a semi-confined impinging jet over a heated flat plate. Experimental data for the pressure distribution and velocity field were obtained. The existence of a velocity equilibrium layer was also investigated. The results found at this preliminary investigation indicate that the level of the logarithmic portion of the velocity law of the wall increases with increasing maximum jet velocity. This fact has also been observed by other authors.

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