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Physical Modelling of Axisymmetric Turbulent Impinging Jets as used within the Nuclear Industry for Mobilisation of Sludges

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ABSTRACT

The impingement of a fluid jet onto a surface has broad applications across many industries. Within the UK nuclear industry, during the final stages of fuel reprocessing, impinging fluid jets are utilised to mobilise settled sludge material within storage tanks and ponds in preparation for transfer and ultimate immobilisation through vitrification.

Despite the extensive applications of impinging jets within the nuclear and other industries, the study of two-phase, solid loaded, impinging jets is limited, and generally restricted to computational modelling. Surprisingly, very little fundamental understanding of the turbulence structure within such fluid flows through experimental investigation is found within the literature. The physical modelling of impinging jet systems could successfully serve to aid computer model validation, determine operating requirements, evaluate plant throughput requirements, optimise process operations and support design.

Within this project a method is illustrated, capable of exploring the effects of process and material variables on flow phenomena of impinging jets. This is achieved via the use of non-intrusive measurement techniques Particle Image Velocimetry (PIV), Ultrasonic Doppler Velocity Profiler (UDVP) and high speed imaging.

The turbulence structure for impinging jets, and their resultant radial wall jets, is presented at different jet-to-plate ratios, jet Reynolds numbers and jet outlet diameters.

1 INTRODUCTION

The UK nuclear fuel reprocessing cycle is very complex involving many stages [1] including the treatment of a highly active waste stream. Prior to final immobilisation within a glass matrix through vitrification, the waste stream is stored in agitated tanks to allow additional cooling, reduce the volume of waste through surface evaporation, and for the preparation of the feed stream to the vitrification process. Particulates in the waste stream are suspended using an array of jet ballasts [2]. The jet ballast operates by applying a set pressure of compressed air into the ballast tank. As the air expands it forces liquor out through the nozzle as a jet which impinges onto the base of the tank inducing re-suspension of any settled solids. Developing a greater understanding of the flow phenomena of these turbulent impinging jets will enable optimisation of plant operations and extension of plant operating envelopes.

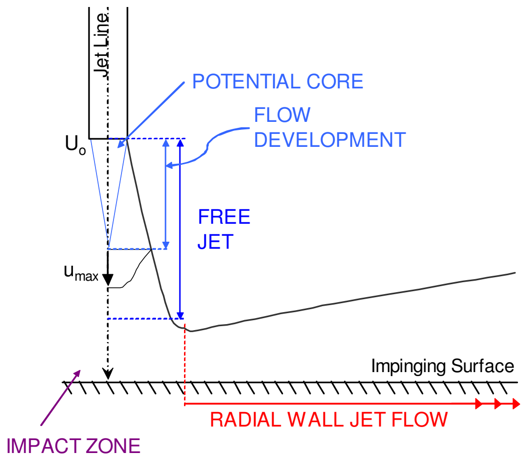

Figure 1: Diagram of an impinging circular jet

The impinging jet is characterised by three regions [3] as depicted in *Figure 1*; the free jet, the impact zone also known as stagnation region/point, and (3) the radial wall jet. The free jet is the fluid flow from the nozzle, where it is allowed to expand freely. The potential core is within the free jet and is the part of the jet where the flow maintains its exit velocity, and is surrounded by a mixing layer which experiences shear, inducing turbulence. In the impact zone, also known as the stagnation or impingement region, the axial velocity decreases rapidly causing an increase in static pressure, resulting in very high convection coefficients and as such impinging jets are extensively used in heat transfer applications. The popularity of the application of this phenomenon has driven considerable interest in this field for many years and is reflected in the vast research reported within the literature. Following impingement, the radial wall jet forms expanding radially away from the impact zone.

Despite extensive applications of impinging jets across many industries including nuclear, the study of two-phase, solid loaded, impinging jets is limited, and generally restricted to computational modelling. Surprisingly very little fundamental understanding of the turbulence structure within these flows through experimental investigation is found within the literature.

2 LITERATURE REVIEW

An extensive body of literature for the heat transfer [4, 5] and fluid flow structure of single-phase impinging jets exist. Publications reporting experimental data for single-phase impinging jets is varied looking at many different aspects of such a system, the variables of interest within this paper are jet line diameter (d), jet-to-plate (h/d) ratios and jet Reynolds number. Cooper et al. [8] found radial wall jets grew linearly with increasing radial distance from the stagnation point and the slope of the jet increased with increasing h/d ratio. Fairweather and Grant [9] later found mean radial wall jet velocities reached a peak at short distances from the impinging surface. The flow structure of free and impinging jets was investigated by Hofmann et al. [8] showed the mean axial velocity for both jets were the same at h/d ratio less than one.

Experimental data for multi-phase impinging jets within the literature is limited. Yoshida et al. [11] found radial mean velocity growth rate of gas-solid jets is slower than the single-phase due to momentum transfer from particles to gas. A key finding from this work was that particles were found to rebound off the impinging plate. It was recorded by Longmire and Anderson [10] that small particles distribute throughout the jet, while the larger remain around the centreline. Each of these investigations of multi-phase impinging jets only considered only one Reynolds number and one h/d ratio.

3 EXPERIMENTAL

3.1 Experimental Set-up, Conditions and Notation

The impinging jet experiments discussed within this paper were conducted in a flume tank [11] with dimensions 1.8m by 1.8m by 1.5m (L x W x H) in the Sorby Fluid Dynamics Laboratory at the University of Leeds. Two jet lines of 10mm (d10) and 20mm (d20) bore were consecutively installed perpendicular to an experimental platform within the flume (see *Figure 2* where d is jet line internal diameter, his height of jet outlet above experimental platform, and D is radial distance from the jet centreline). Trials were performed at different jet line diameter (d) jet-to-plate ratios (h/d) and jet Reynolds number.

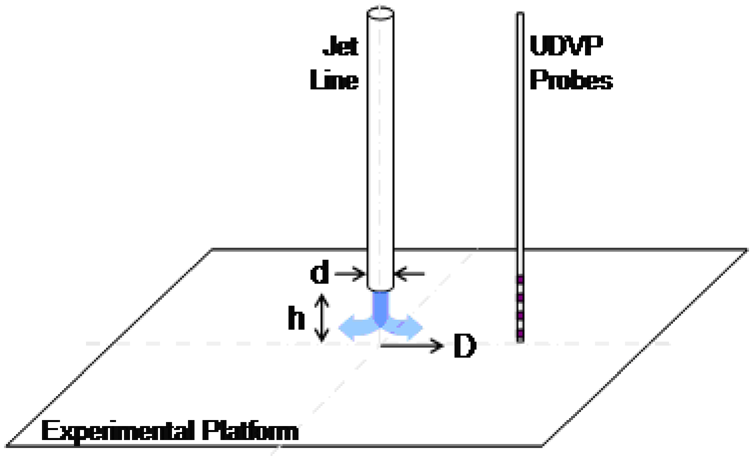

Figure 2: Schematic representation of the Impinging Jet Line and UDVP Experimental Set-up

Ultrasonic Doppler velocity profiling (UDVP), an acoustic technique which enables investigation of coherent flow structures in opaque flows, was used to record the near-instantaneous downstream horizontal velocities of the resultant radial wall jets. The measurement is near-instantaneous because of a short delay between each transducer element recording a profile. An array of five 2MHz ultrasonic transducers were mounted parallel to the experimental platform, stacked one above the other, at intervals of 10mm between the transducer centrelines. The horizontal velocities were recorded at 128 measurements positions for a total of 1000 profiles per transducer.

3.2 Experimental Methodology

The experimental design within the project reported here for the physical modelling of turbulent impinging jets has been developed to explore the effect of process variables jet line diameter (d), jet-to-plate spacing (h/d), and jet Reynolds number. The levels for these variables which have been investigated are shown on *Table 1*.

Table 1: Process variables investigated

Process Variable	Settings
Jet line diameter (d)	10mm (d10) and 20mm (d20)
Jet-to-plate spacing (h/d ratio)	1, 5 and 8
Reynolds number (Re)	35,000 and 65,000

4 RESULTS AND DISCUSSION

Time-averaged radial wall jet horizontal velocity profiles were generated using UDVP as discussed and are reported in *Figures 3, 4* and *5*. The data presented here was initial data generated during the system and procedural development of this project. It is important to note that using the UDVP configuration as described only the horizontal velocity component is measured.

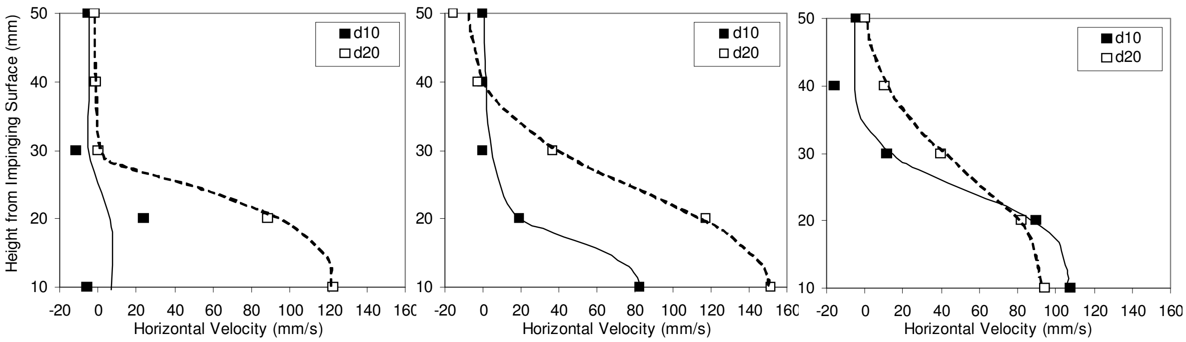

Figure 3: Time-averaged radial wall jet horizontal velocity UVP profiles for impinging jets of 10mm (d10) and 20mm (d20) diameter for h/d ratio of 1 and Reynolds number 35,000; (a) D/d ratio = 5, (b) D/d ratio = 10, (c) D/d ratio = 15

Figure 3 displays horizontal velocity profiles at three non-dimensional radial distances from the jet centreline as a function of jet line diameter, d. A difference in the development of the resultant radial wall jets are apparent and differ depending on d. For d10 the radial wall jet is developing, both jet height and peak horizontal velocity increasing with increasing D/d (from *3(a)* through to *3(c)*), and move radially away from jet centreline, as was seen by Cooper et al. [6]. The radial wall jet for d20 is seen to be growing from *3(a)* to *3(b)* similar to the d10 jet development, but by D/d of 15 the peak horizontal velocity is already decreasing and the jet height increasing.

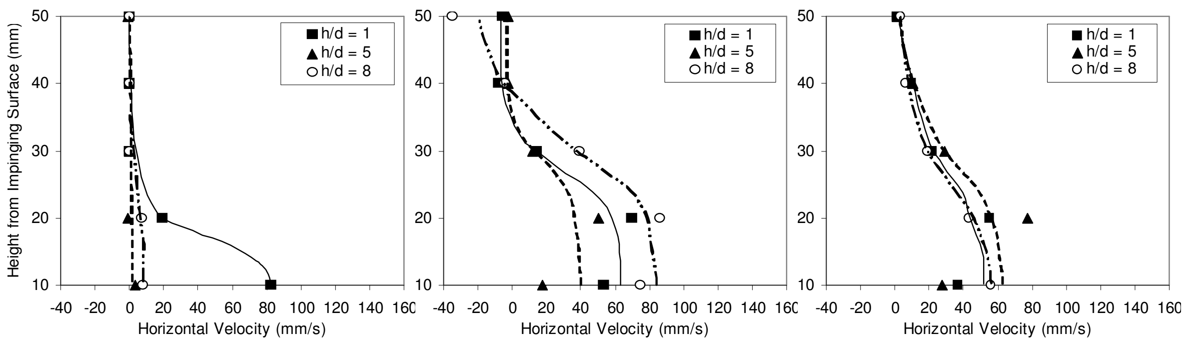

Figure 4: Time-averaged radial wall jet horizontal velocity UVP profiles for impinging jets of 10mm (d10) diameter at Reynolds number 35,000; (a) D/d ratio = 10, (b) D/d ratio = 20, (c) D/d ratio = 30

Horizontal velocity profiles at different jet-to-plate spacings (h/d) for d10 and Reynolds number of 35,000 are plotted in *Figure 4*. For h/d of 1, the wall jet has developed and by D/d of 30 (*Figure 4(a)*) the horizontal velocity component has decreased. All velocity profiles displayed show a peak at short distances from the impinging surface which is in agreement with findings by Fairweather and Grant [7].

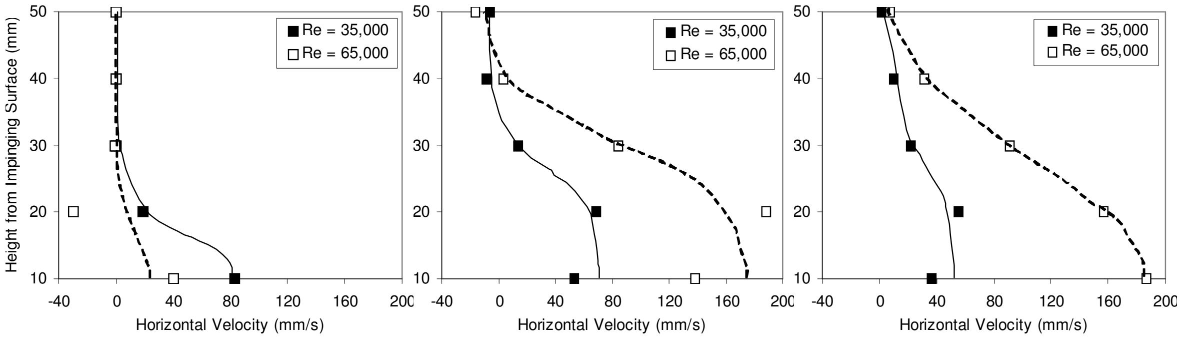

Figure 5: Time-averaged radial wall jet horizontal velocity UVP profiles for impinging jet of 10mm (d10) diameter at h/d ratio of 1; (a) D/d ratio = 10, (b) D/d ratio = 20, (c) D/d ratio = 30

A change in jet Reynolds number has an influence on the resultant radial wall jet as seen on *Figure 5*. At the lower of the two Reynolds numbers investigated here it is seen that by D/d of 20 the wall jet velocity is decaying quite substantially in comparison to the higher Reynolds number tested. When the Reynolds number was 65,000, the wall jet growth can be clearly seen as D/d increased from 10 to 30.

5 CONCLUSIONS

Impinging turbulent jets at different jet line diameter (d), jet-to-plate spacing (h/d), and jet Reynolds number have been experimentally investigated and the resultant radial wall jet horizontal velocities measured using ultrasonic Doppler velocity profiler (UDVP). As the jet line diameter was increased from 10mm (d10) to 20mm (d20) the radial wall jet peak velocity increased, as did the height of the jet, concurring with data within the literature. When altering the jet-to-plate (h/d) spacing the difference between the horizontal velocity profiles were more pronounced at the lowest D/d presented of 10. Additionally increasing the jet Reynolds number from 35,000 to 65,000 saw a significant increase in the radial wall jet peak velocity and jet height.

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