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Model study of dissipation of jets in deep wells

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This paper presents an experimental investigation of a submerged round jet discharging vertically into a deep well. The research work was concentrated on two positions of the jet: (*a*) impingement at the centre of the well; and (*b*) impingement near the upstream side of the well. Square and rectangular shaped wells were tested for various pipe heights and well dimensions. Using a laser Doppler anemometer, velocity distributions were measured in the vertical and horizontal planes inside the well and compared with those for the free jet and the wall jet. The flow pattern and velocity decay of the jet were studied while varying the ratios of well height to pipe diameter between the practical limits of 6 to 16. Based on these results, an optimum size for a deep well has been indicated, with satisfactory prototype performance.

Keywords: drainage & irrigation; hydraulics & hydrodynamics; models (physical)

Notation

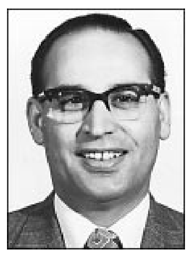
a	pipe height above floor of well
b	length of well
C	coefficient of jet
D	pipe diameter
d	depth of well
F_0	$\boldsymbol{U}_0/(\boldsymbol{g}D)^{1/2}$ = Froude number of jet
$\boldsymbol{g}$	gravitational acceleration
h	depth of water in channel downstream of well
h_2	downstream depth in jet dissipation channel
L	lateral width of the side jet velocity profile from centreline of well
n	exponent of power law
R_0	$\boldsymbol{U}_0 D/v$ = Reynolds number of jet
$\boldsymbol{U}$	maximum horizontal velocity in well
$\boldsymbol{U}_0$	jet exit velocity
$\boldsymbol{u}$	horizontal velocity in well or channel
$\boldsymbol{V}$	maximum vertical velocity in well
$\boldsymbol{v}$	vertical velocity in well
w	width of well
x	horizontal distance from centreline of pipe
Y	height above floor of well or channel
y	vertical distance from pipe outlet
z	lateral distance from centreline of well or channel
v	kinematic viscosity of water
ϕ	angle of jet impingement

Introduction

Vertical stilling wells and deep pools are normally used for high-velocity discharge from pipe outlets. The pipe enters the well vertically, and in some cases, with a control valve attached to the end of the pipe. The jet spreads horizontally along the bottom of the well and then rises vertically where it is dispersed and discharged with a low velocity into the downstream channel. Few records were found of fundamental work on the behaviour of such a jet or the effect of the depth and width of the well or channel upon the dissipation of the jet entering it.

2. The US Bureau of Reclamation (USBR) has utilized the vertical stilling well as an efficient means of energy dissipation. Its potential to receive and still discharges from manifolded outlets more economically than a stilling basin has been recognized. In the past, individual model studies have been used to develop each specific stilling well design. In 1970 a research programme was undertaken by the USBR to develop general design criteria for these wells. Their work[1] presented design rules for determining optimum well geometry with corner fillets and corner angles, based on the design discharge and diameter of the standard sleeve valve.

3. Some concrete erosion of prototype stilling well walls and floors has been reported. Because of such experience, engineers have elected, on recent designs, to protect the floor and walls with stainless-steel plate. While these investigations have contributed to a better understanding of design considerations, the details of the flow and the behaviour of the jet have not been studied. Also, consultants have reported to the principal author, problems with the operation of such wells. Designers still lack guidance on how to vary the size of the well if the fillets and corner angles are omitted. These devices are difficult to construct and maintain, especially in developing countries where there is a shortage of skilled construction workers. Furthermore, experiments by Vasanthakumaran[2] have revealed that whereas the surface waves in the well and downstream channel were reduced with the inclusion of fillets, the velocity in the channel remained relatively high.



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4. The present research on jet dissipation in vertical deep wells has followed and complemented previous research programmes on water jets at the University of East London.[3–5] The main objectives of the research were to carry out investigations into jet dissipation in deep pools and vertical wells, in order to provide an insight into the behaviour of such jets in stilling arrangements of pipe outlets. Wells of square and rectangular cross-sections were used in the tests, and measurements of horizontal and vertical velocity profiles were carried out using a laser Doppler anemometer (LDA). Experiments were carried out to measure the velocity profiles and the variation of the maximum velocity decay of the jet as it travelled from the pipe outlet, along the floor and up the side wall of the well before it deflected into the downstream channel flow. The flow pattern and decay of the jet were studied while varying the ratios of jet diameter to well width and height between the limits of 6 to 16. The downstream channel depth was kept constant at a minimum of three pipe diameters, $3D$. Two values of the Froude number F_0, 8 and 15, were mainly used. F_0 is defined by the equation

$$F_0 = \frac{\boldsymbol{U}_0}{(\boldsymbol{g}D)^{1/2}} \tag{1}$$

where $\boldsymbol{U}_0$ is the jet exit velocity, D is the pipe diameter and $\boldsymbol{g}$ is the acceleration due to gravity. The velocity profiles have been compared with those for a free jet and a wall jet as given by Schlichting[6] and Rajaratnam.[7]

Analytical background

5. The design of stilling wells, like the design of many hydraulic structures involving jets whose expansion is limited by complex boundary conditions, will probably for a long time to come be based on the results of experimental model tests. The details of the flow are so complicated that no current theory could describe them. However, the main features of certain jets have been analysed, and the results, while not directly applicable, are of great help in explaining the motion of the jet from a pipe outlet.

6. Using Prandtl's mixing length theory, Tollmien,[6,8] solved the fundamental equations of turbulent motion of a round jet originating from a point source and diffusing into ambient surrounding fluid. He showed that the central velocity of the jet $\boldsymbol{U}$ is inversely proportional to the distance x, that is

$$\frac{\boldsymbol{U}}{\boldsymbol{U}_0} = C\left(\frac{D}{x}\right)^n \tag{2}$$

where $\boldsymbol{U}_0$ is the jet exit velocity, C is the jet coefficient, D is the orifice or pipe diameter and n is the power index. The value of C has been found experimentally to be variable depending on the effect of the boundary layer in the nozzle. Based on experimental results a mean value of 6·5 has been recommended. Kuethe[8] extended Tollmien's work to the case of a jet with a finite source and established that the length of potential core is about five jet diameters downstream of the orifice. The result agreed with experiments of free air jets over a wide range of Reynolds numbers, R_0.[6] R_0 is defined by the equation

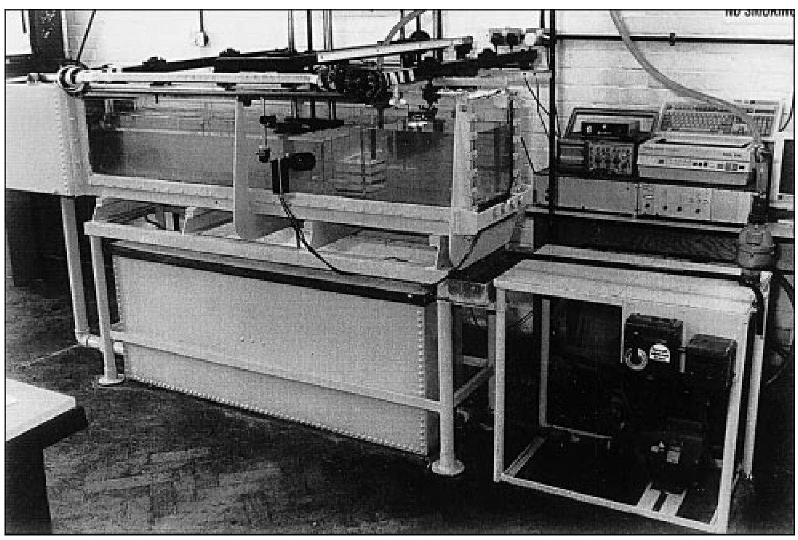
$$R_0 = \frac{\boldsymbol{U}_0 D}{\nu} \tag{3}$$

7. The flow of a round jet impinging vertically on a plate and spreading radially over it has been termed the wall jet and analysed by Glauert.[9] An experimental investigation of the radial wall jet has been carried out by Bakke.[10] Measurements of velocity profiles were made at distances 1 to 20 times the jet diameter. At these distances, the profiles were similar and the rate of decay of the jet followed a power law which was in fair agreement with Glauert's prediction. Studies of the characteristics of the velocity and pressure fields in similar jets have also been conducted by a number of other investigators.[4,11–13] A general account of impinging jets was recently made by Vischer and Hager.[14]

Apparatus and experimental conditions

8. The work was carried out mainly in special water jet equipment, shown in Fig. 1, consisting of a pipe discharging into a glass flume 1800 mm long × 300 mm wide. Various pipe diameters of 13, 16, 25 and 50 mm were used. Perspex walls were inserted into the channel to form the well. The flow was supplied by a centrifugal pump and measured by a Kent digital meter. The depth of flow in the channel was controlled by means of an adjustable tailgate situated in the outlet tank.

Fig. 1. Experimental equipment



9. The LDA technique was adapted for measurements of mean velocities and turbulence characteristics without any interference in the flow, and utilized for the investigation of the complex three-dimensional circulating flow which was experienced in the well. The use of a Bragg cell in the system made possible instantaneous measurements of reverse flows in the circulation regions. Information from these units was fed into a computer where the mean and root-mean-square values of the velocity were calculated. These mean values were for about a thousand measurements of instantaneous velocity taken at a given point. Air entrainment was visible for shallow wells of 2–4*D* depth for which no accurate measurements could be taken.

10. To have some indications of the scale effects, experiments were also conducted in a larger channel 600 mm wide, with pipes of 50, 75 and 100 mm diameter. The flow conditions were observed to be similar to those in the 300 mm channel. The range of tests carried out on the 600 mm channel was not as extensive as the 300 mm tests due to the optical limitations of the LDA in measuring flows in channels wider than 450 mm.

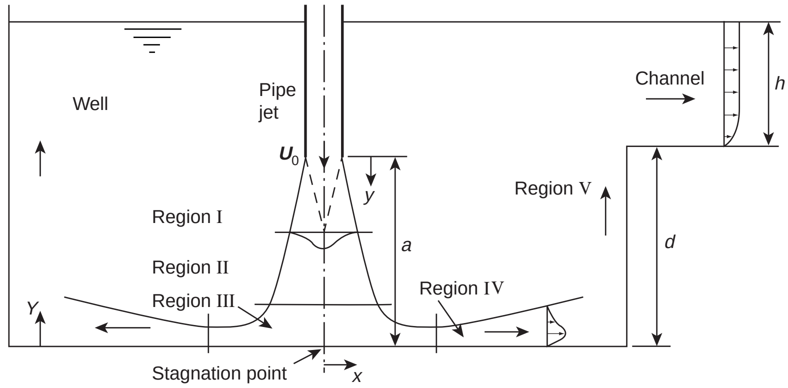


Fig. 2. Schematic diagram of central jet flow in well

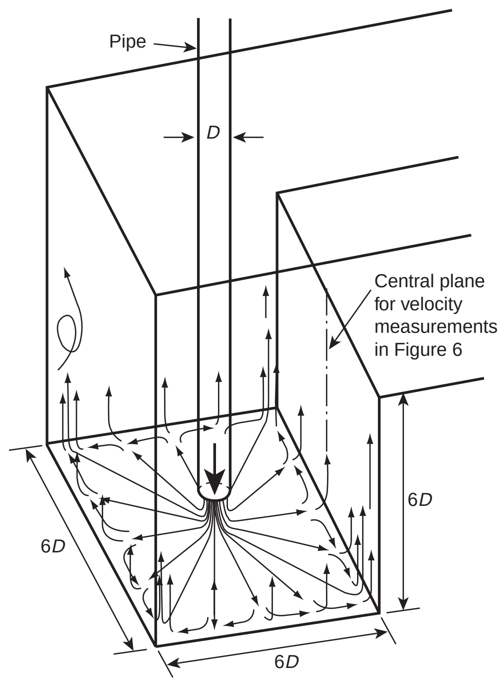


Fig. 3. Flow along the floor and sides of the well

General flow pattern

11. When a round water jet discharges vertically into a deep well, a complicated three-dimensional flow pattern is formed, which varies from section to section across the width of the well. Despite this complexity, five regions may be generally identified along the centre plane as shown in Fig. 2. In region I, the jet issues into a slow-moving fluid and expands in a similar way to a submerged round jet in an infinite surrounding fluid. For pipe heights *a* of up to 5*D* above the floor of the well, this region resembles that of the potential core of the submerged jet. The mixing process between the jet and the surrounding fluid causes part of the latter to be carried downward with the jet into region II where recirculation is formed.

12. In region III, the jet is transformed into a thin stream which flows horizontally and radially in all directions. When the stream reaches the side walls of the well, it is deflected partly upwards and partly laterally towards the four corners of the well (Fig. 3). Strong currents flow up the corners resulting in upsurges above the mean water level. At each corner the rising stream then turns through 180° and plunges towards the centre of the well thus creating wave action and turbulence in the downstream channel.

13. In region V, the decayed jet flows upward along the vertical sides of the well, and on the downstream side of the well turns horizontally towards the channel downstream. Complex recirculation regions are created inside the well, as indicated in Fig. 4. The flow patterns near the sides of the channel and well have some resemblance to that along the centreline but it differs in its recirculation zone near the top of the well.

Distribution of velocity in well

14. In order to study the details of the flow pattern, the distribution of mean vertical velocity was measured across the central plane of the well at various heights above the floor of the well. Typical velocity profiles for a central jet in a square well of side 6*D* and depth 6*D* caused by the jet exit velocity, as shown plotted in Fig. 5. The pipe height *a* equals 6*D* and the depth of water in the channel downstream of the well *h* equals 3*D*. At the pipe outlet the distribution is characterized by a constant high jet velocity, decreasing sharply at the nozzle boundary. The surrounding fluid moves with a

slow velocity in the same direction. At four diameters above the floor of the well, the maximum velocity decreases gradually to zero at about 2*D* from the centre of the jet and then reverses in direction to rise along the vertical sides of the well. Further downward, at 3*D*, 2*D* and 1*D* above the floor, the velocity profiles become flatter but the general shape remains unaltered. The profiles, however, were not found to be similar. The reduction in maximum velocity is nearly 20% over a depth of 5*D*. The corresponding rate of spreading of the jet boundary is estimated as 12°, which is the same as that of a free round jet discharging into the atmosphere.[8]

Decay of maximum jet velocity

Decay of central jet

15. A series of experiments was carried out to measure the variation of the maximum velocity decay in the central jet as it travels downward from the pipe outlet along the centreline of the well, radially along the floor of the well, and finally up the side wall of the well before being deflected into the downstream channel. The experiments were conducted for various sizes of jets and typical results for a 16 mm jet discharging into a square well are now described.

16. The measurements were taken along the centreline for a wide range of pipe heights above the floor of the well, ranging from one to 16 diameters. In these experiments a well of square section was used (9*D*) and two well depths of 12*D* and 16*D*. The width of the channel was the same as the well and the depth was kept constant at 3*D*. The variation of maximum velocities is shown in Fig. 6 for the well with a depth of 12*D*, and Fig. 7 for the well of a depth of 16*D*. It can be seen that the higher the pipe the greater the drop in velocity, reaching 30% of the original velocity for a height of 14*D*. For the deeper well of 16*D* depth the corresponding reduction is 90% of the original velocity. Negative velocities occur at the entry of the channel due to the formation of a small recirculation zone.

17. In region IV, for both wells, a similar percentage of velocity is lost in the horizontal distance travelled along the floor of the well before deflecting upward. The combination of losses in vertical downward and horizontal distances travelled before deflecting upwards at the corner of the well is around 70% of the jet exit velocity. The percentage of dissipation is almost the same for all jet heights for the wells of depth 12*D* and 16*D*. Theoretically, for y/D greater than 4, the central maximum velocity decreases in a similar manner to that of a free round jet given by equation (2). The average value of C for various pipe heights,

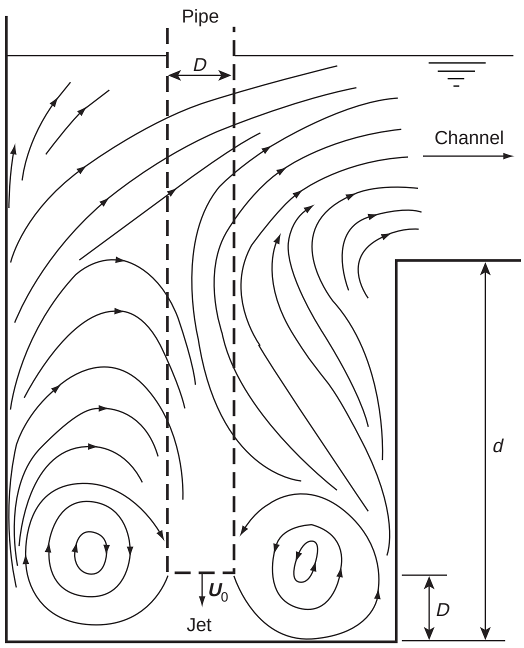


Fig. 4. Flow pattern in well for pipe height 1D

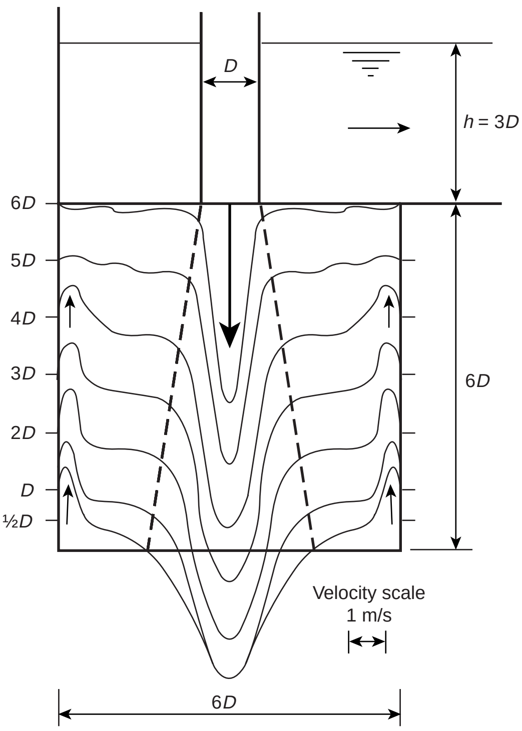


Fig. 5. Velocity profiles at various heights above the floor of the well of depth 6D

$8 < a/D < 18$, is 5·3 compared with a mean value of 6·5 for a free jet.

Decay of side jet

18. Experiments were carried out on a jet placed near the upstream side of the well (Fig. 8), with the jet discharging at one diameter above the bottom of a square well and one diameter from the side. The range of depths (covered in the well) was varied from two diameters to 16 diameters. Velocity measurements were taken in the vertical and horizontal planes inside the well and in the

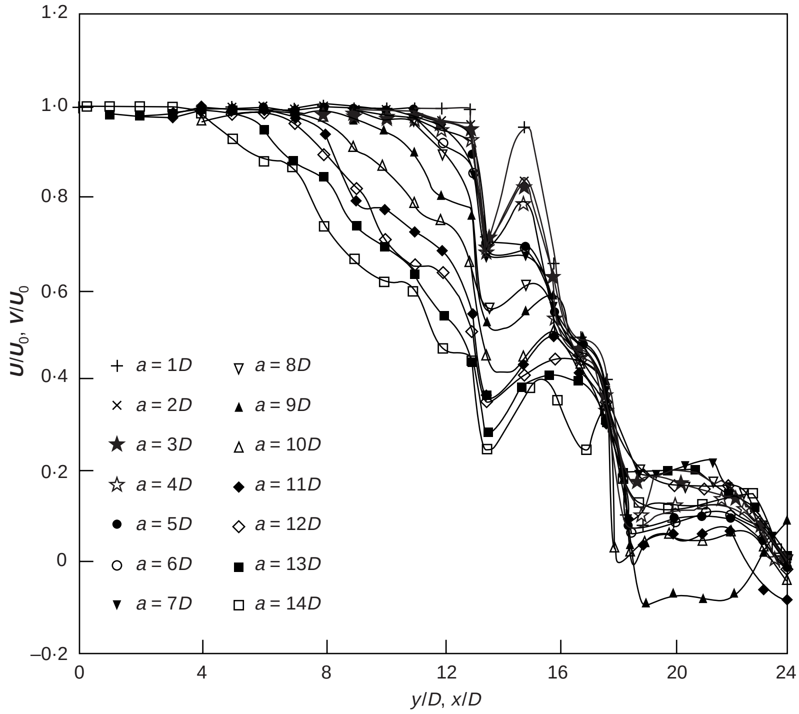


Fig. 6. Maximum velocity decay in square stilling well of 12D depth

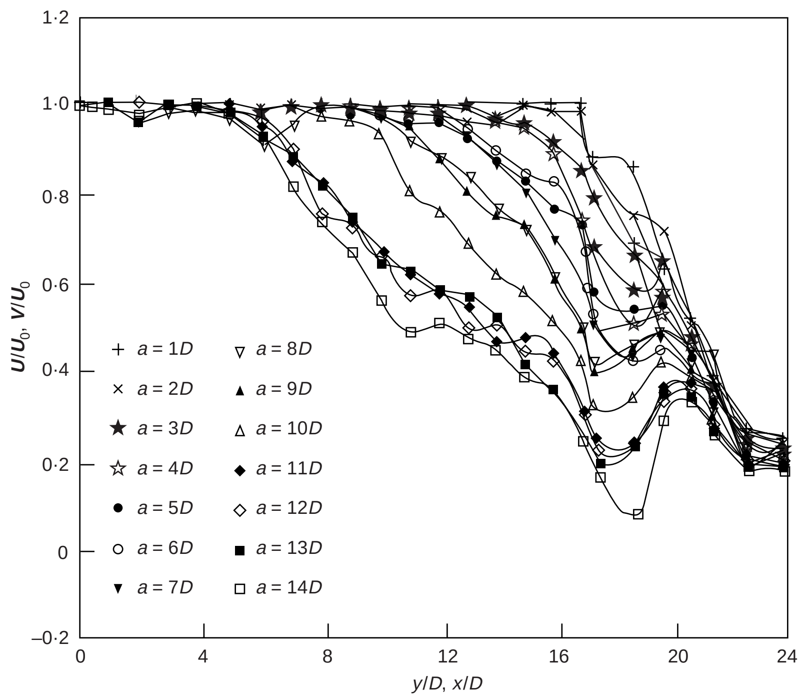


Fig. 7. Maximum velocity decay in square stilling well of 16D depth

downstream channel. The Froude number of $F_0 = \boldsymbol{U}_0/(\boldsymbol{g}D)^{1/2} = 15$, and the depth of water in the channel, $h = 3D$, were kept constant for all the tests.

19. The decay of maximum velocity as the side jet travels along the bed and downstream side of the well is plotted non-dimensionally in Fig. 9. It is seen that for all depths of the well the reduction of velocity follows practically the same curve and its value reaches about 5–10% of the initial jet velocity in the downstream channel. The results show that for distances $2 < x/D < 9$ along the bottom of the well the velocity variation is approximately linear for each depth of the well and is in agreement with the free jet equation (2): $\boldsymbol{U}/\boldsymbol{U}_0 = C(D/x)^n$, where $n = 1$, the value of C varying between 0·83 and 1·05 for the range of well depths 2–16D. The corresponding value of C for a free submerged jet is 6·5 and for a radial wall jet is 1·12. The results are compared with values for other jets in Table 1, the figures being lowest

Table 1. Variation of C and n with impingement angle

Experiment	Jet height: a/D	Impingement angle: ϕ°	C		n
Present data:					
Central jet in well	8–18	90	5·30		1
Side jet in well:					
$d/D = 2$	1	90	0·83		1
$d/D = 16$	1	90	1·05		1
Naib and Sanders[4]:					
Water jet in channel	0·7–6·0	45	2·32		1·02
		60	2·05		1·09
		75	1·97		1·22
		90	1·79		1·45
Naib[11]:					
Air jet on flat plate	<1	0	7·0		1
		15	4·0		1
		30	2·8		1
		45	2·4		1
Bakke[10]:					
Radial wall air jet	0·5	90	1·12		1·12
Beltaos and Rajaratnam[12]:					
Air jet on flat plate	15–47	20	3·8		1
		30	3·0		1
		45	2·5		1
		60	2·0		1
Yakovlevskii and Krasheninnicov[13]:					
Air jet on flat plate	3·5–10·0		$h_2/D = 3{\cdot}5$	$h_2/D = 10$	
		30	—	2·8	1
		45	2·3	—	1
		60	2·0	2·0	1
		90	1·2	1·5	1

for the side jet, so dissipation seems to be weak as compared with conventional means. In Table 1, ϕ is the angle of jet impingement to the horizontal and h_2 is the downstream depth for jet dissipation in channels.

Effects of well shape and jet height

20. To study the effect of the shape of the well, experiments were conducted for two cross-sections

(*a*) a rectangular well of length 6*D*, depth 6*D*, and width 12*D*
(*b*) a square well of length 6*D*, depth 6*D* and width 6*D*.

In each case the width of the channel was the same as that of the well and the downstream depth was contained at 3*D*. By comparing the results of the two wells it was deduced that the rate of the dissipation of velocity is increased with a square well. However, raising the height of the jet above the bottom of the well had little effect on the decay rate. Comparison of the results and observations of the water surface profiles for both sizes of jets and wells indicate that, although similar reduction in velocity is achieved, the flow is far more steady and calm for the larger well of 12*D* width.

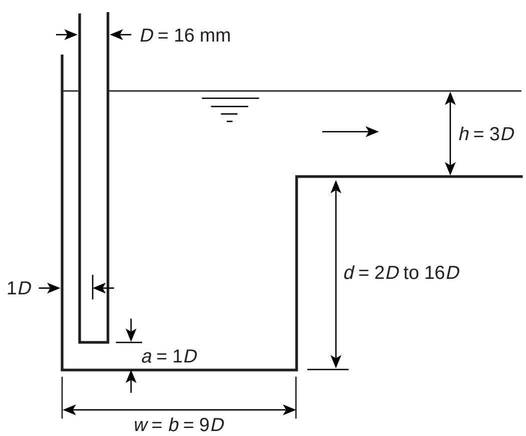


Fig. 8. Side jet position in the square well

Velocity profiles

Corner velocity profiles in well

21. Measurements of vertical velocity in two corners of the well p and r and at two points q and s along the centreline are shown in Fig. 10. At the corners all the flows are upwards and the strong currents rise to the water surface

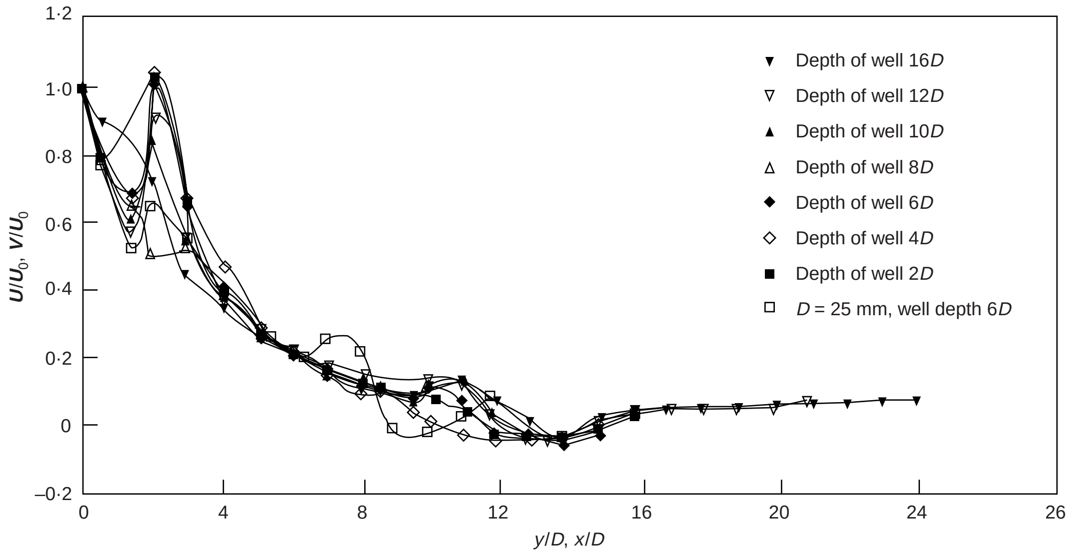


Fig. 9. Comparison of maximum velocity decay in square wells

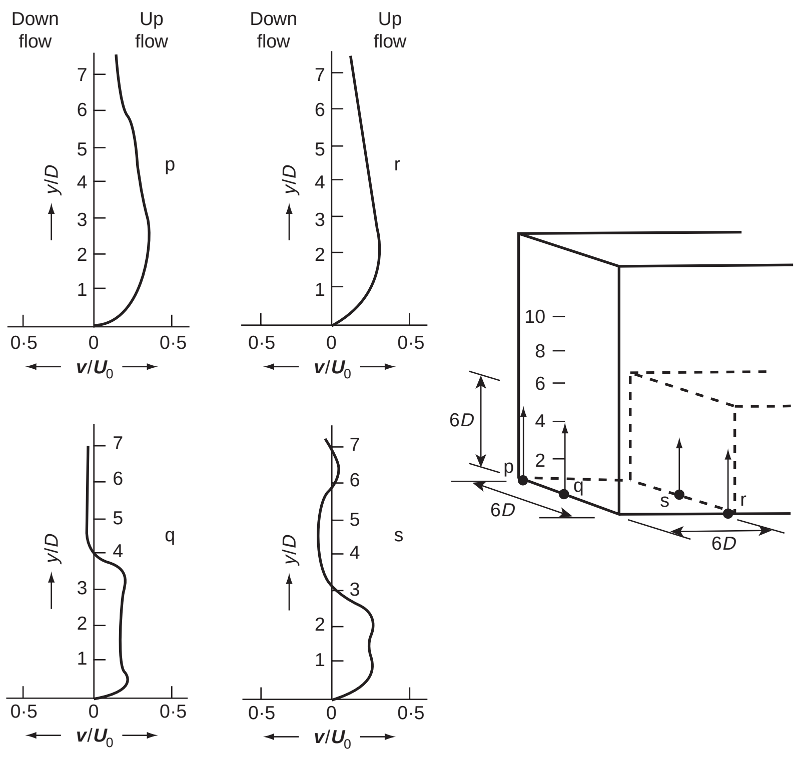


Fig. 10. Velocity profiles at corners and mid-points in a well of 6D depth

and plunge back into the pool creating water 'boils' as high as 1·5D above the water line. In contrast, at points q and s along the centre plane of the well the stream rises roughly to about 3D from the floor and recirculates in the lower half of the well. The corner currents form a second recirculation region in the upper half of the well.

Lateral and vertical velocity profiles in well

22. Figure 11 shows the lateral distribution of velocity of the jet across the width of the well of depth 4D, at a height of 0·1D from the floor of the well and for distances up to $x/D = 7$. Directly under the impact region of the jet, the velocity is zero at the stagnation point. At 1D distance from the centre of the jet, the velocity reaches a maximum value and then decreases gradually downstream where it becomes uniform at about 7D distance from this particular configuration. The velocity profiles are plotted non-dimensionally and compared with the free jet profile in Fig. 12.[6] It is seen that the profiles vary from section to section and agreement is only achieved at $x = 2D$. Evidence is given in Fig. 13 where it is clear from the

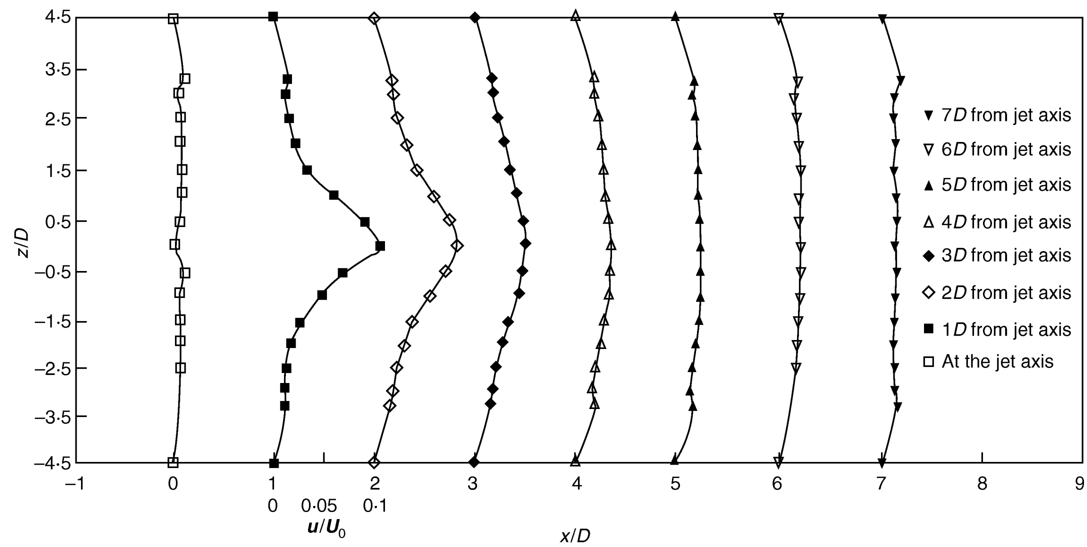


Fig. 11. Lateral velocity profiles for side jet in horizontal plane 0·1D above the well bed

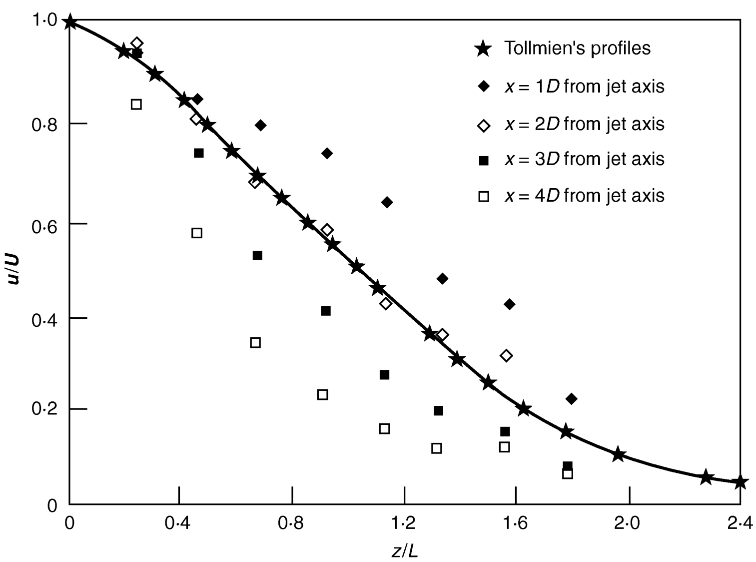


Fig. 12. Comparison of lateral velocity profiles with Tollmien's free jet profile

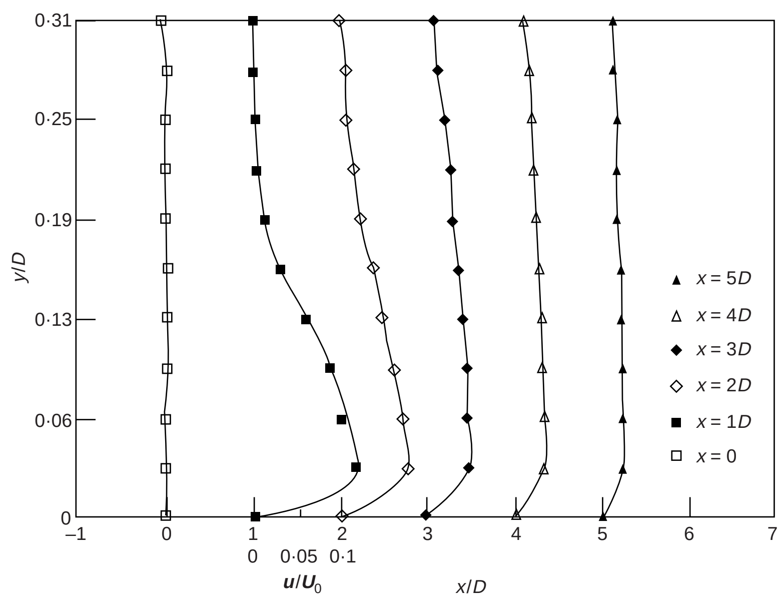


Fig. 13. Vertical velocity profiles along the floor of the square well

vertical profiles that the velocity inside the well is very small at that height for distances up to $x/D = 5$.

Statistical analysis and application

Optimum size of well

23. The statistical analysis of the results (Fig. 14) shows clearly that for each dissipation rate up to 70%, the distance x/D is minimum for a depth of well equal to 8–10*D*. This well produced the shortest distance for maximum velocity dissipation from the centre of the jet for Froude numbers up to 15. No accurate measurements could be taken at very high velocities and in shallow wells because of air entrainment which affected the LDA equipment. Therefore the effects of cavitation and abrasion for these cases could not be quantified. However, the turbulence levels in the deep well and downstream channel were observed for all flows and were found to be minimum for well depths of ten pipe diameters. Tests on a model in a mobile bed channel showed little erosion downstream. From these results it could be concluded that for 9*D* square wells of depth 10*D*, a substantial dissipation of the maximum jet velocity of approximately 95% is achieved. A minimum flow depth of 3*D* must be maintained in the downstream channel.

Design and prototype performance

24. The findings were used for the design of two stilling wells. The first concerned a pipe of 0·75 m diameter carrying a discharge of 5 m^3/s into a well of 7 m side × 7·5 m depth. The second design was for a pipe 0·6 m diameter discharging 1·3 m^3/s under a pressure head of 30 m into a well of 5 m diameter × 8 m height. Pressure surges were predicted in the second design and hence the depth was increased by about 25%. Model investigations and subsequent construction showed both designs to be satisfactory and no cavitation was observed during model investigations.

Conclusions

Dissipation of central jet in deep wells

25. The conclusions for the dissipation of a central jet in deep wells can be summarized as follows.

(*a*) A complicated three-dimensional flow pattern occurs, which varies from section to section across the width of the well.
(*b*) The radial flow along the floor of the well is primarily diverted into the four corners, resulting in strong currents and upsurges above the water surface.
(*c*) The horizontal velocity near the bottom edge of the well is practically the same for all jet heights tested.

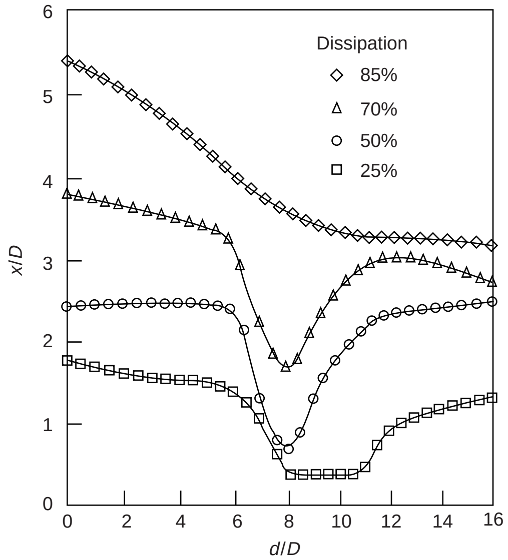


Fig. 14. Statistical analysis of velocity head dissipation for the side jet

(*d*) Greatest velocity reduction, up to 60%, occurs as the jet changes from horizontal to vertical upflow along the four sides of the well.
(*e*) By comparing the results for a square well with those of a wider rectangular well, it was deduced that the rate of dissipation of velocity and level of turbulence are increased by decreasing the width of the well.
(*f*) The level of turbulence both in the well and downstream channel increases with decreasing water levels in the channel.

Dissipation of side jet in deep wells

26. The conclusions for the dissipation of a side jet in deep wells can be summarized as follows.

(*a*) For well depths up to 16*D*, it was found that the decay of maximum velocity of the jet follows practically the same curve and its final value in the downstream channel is 5–10% of the initial velocity of the jet.
(*b*) For distances $2 < x/D < 9$ along the bottom of the well the velocity variation is approximately linear for each depth of the well and is in agreement with the theoretical equation for the free round jet: $\boldsymbol{U}/\boldsymbol{U}_0 = C(D/x)$.
(*c*) The value of *C* varies between 0·83 and 1·05 for the range of depths up to 16*D*. The corresponding value for *C* of a wall jet is 1·12.

27. Applying the results of the side jet to the design of deep stilling wells, the indications are that the fastest dissipation rate occurs when the depth of the square well is about 10*D* and its width 9*D* for Froude numbers up to 15. This produces a steady water surface with little wave action in the downstream channel having a minimum flow depth of 3*D*.

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