An experimental investigation of the hysteresis phenomenon and effects of gap on curved wall jet separation.

P. K. Arora
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AN EXPERIMENTAL INVESTIGATION OF THE
HYSTERESIS PHENOMENON AND
EFFECTS OF GAP ON CURVED
WALL JET SEPARATION

A THESIS

Submitted to the Faculty of Graduate Studies through
the Department of Mechanical Engineering in partial
Fulfillment of the Requirements for the Degree
of Master of Applied Science at the
University of Windsor.

by

P. K. Arora

M.E., The University of Roorkee, India, 1964.

Windsor, Ontario, Canada
1967

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ABSTRACT

The hysteresis phenomenon and angular position of separation were studied in a two-dimensional curved wall jet with different initial gaps between nozzle exit and leading edge of the wall. Nine different nozzle-curved wall combinations were used.

With an increase in the gap parallel to the nozzle axis, the loci of positions of the jet attachment and detachment and the approximate free jet boundary came closer together and the jet deflection became less stable. The maximum allowable gap parallel to nozzle axis was proportional to wall radius.

An increase in gap reduced angular position of separation ($\theta_{sep.}$), the gap parallel to the nozzle axis having less effect than perpendicular gap. The angle of separation initially increased with the product of Reynolds number and ratio of jet slot width to wall radius and finally approached a constant value. Almost the same effect was observed with different gaps.
ACKNOWLEDGEMENTS

The author is indebted to Prof. W. G. Colborne for providing the opportunity to pursue this investigation and for his continued support and encouragement.

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NOTATION

\( t \)  
Jet nozzle width (ft.).

\( R \)  
Radius of a wall (ft.).

\( h \)  
Distance between nozzle lip and leading edge of deflection surface, parallel to the axis of the nozzle (ft.). See Fig. 1.

\( h_{\text{max}} \)  
Maximum allowable value of \( h \).

\( v \)  
Distance between nozzle lip and leading edge of deflection surface, perpendicular to the axis of the nozzle (ft.). See Fig. 1.

\( v_D, v_A \)  
Value of \( v \) at detached and attached position respectively.

\( m \)  
Difference between \( v_D \) and \( v_A \) at a given \( h \).

\( P_a \)  
Atmospheric pressure (lbs./ft.\(^2\)).

\( P_s \)  
Static pressure on the wall (lbs./ft.\(^2\)).

\( P_t \)  
Total pressure in the jet at the nozzle exit (lbs./ft.\(^2\)).

\( \rho \)  
Density of the fluid (slugs/ft.\(^3\)).

\( \nu \)  
Kinematic viscosity (ft.\(^2\)/sec.).
\( \theta \) Angular position measured from the leading edge (degrees).

\( \theta_{\text{sep.}} \) Angular position of separation.

Re Reynolds number = \[ \left( \frac{(P_T - P_a) R_t}{\rho \nu^2} \right)^{1/2} \]

Cp Pressure coefficient = \[ \frac{(P_a - P_s) R}{(P_T - P_a) t} \]

Note: Superscript prime denotes dimensionless value in terms of the jet slot width. For example, \( \nu' = \frac{\nu}{t} \).
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CHAPTER I

INTRODUCTION

When a curved wall surface is placed such that a jet emerges tangential to it, it is seen that the jet flows along the curved surface. This phenomenon is known as 'Coanda Effect' or 'Coanda Jet Deflection'.

The nature of the jet flow is complex. Turbulent mixing is predominant in the major outer part of the flow. But near the wall surface, the viscous effects have to be accounted for. Newman (Ref. 1) and Fekete (Ref. 2) have done considerable work on jet flow over a cylinder without a gap between the nozzle and curved surface. Korbacher (Ref. 3) and Benner (Ref. 4) studied gap effects by measuring the force acting on, and the surface pressure distribution over, a quadrant surface.

Recently, Paranjpe (Ref. 5) investigated the effects of a gap on the velocity profile, position of jet separation, static pressure distribution and also studied the hysteresis phenomenon. He kept the nozzle width and wall radius constant. The present investigation studies the hysteresis phenomenon and gap effect on wall jet separation using different nozzle-curved wall combinations. The surrounding fluid was stationary and
the flow was in the incompressible range.
CHAPTER II

LITERATURE SURVEY

The material covered in this chapter summarizes briefly the existing literature and is included in the report for the sake of completeness and ease of reference. Jet flow over a curved wall without an initial gap is considered first in the following sections. A knowledge of this flow is necessary for our investigation.

2.1 IDEAL FLUID FLOW

The bending of a jet sheet is produced by a pressure difference acting across it. Considering an element in a two dimensional flow of a thin jet \( t \ll R \) of an ideal fluid and equating the centrifugal and the pressure forces which are in radial equilibrium, the pressure coefficient \( C_p \) is expressed as:

\[
C_p = \frac{(P_t - P_a)R}{(P_t - P_a)t} = 2
\]

The experimental results of Korbacher (Ref. 3) agree well with equation (2.1) for small values of \( \theta \). But the values obtained by Newman (Ref. 1) and Fekete (Ref. 2) are less than that predicted by equation (2.1).
2.2 REMARKS ON REAL JET FLOW

The real fluid jet continuously entrains fluid from the surroundings. Thus the jet width increases and the fluid velocity decreases with an increasing $\theta$. In consequence, the pressure at the surface which is initially lower than $P_a$ due to the flow curvature, tends to approach $P_a$ as the jet velocity decreases. Hence the entrainment of the surrounding fluid produces the pressure rise that finally causes the jet to separate from the surface. This emphasizes the necessity of including the process of entrainment in any theoretical analysis.

2.3 NEWMAN'S ANALYSIS (DIMENSIONAL APPROACH)

The following parameters are sufficient to define an incompressible jet flow over a curved surface:

$$(P_a - P_s), (P_T - P_a), t, R, \nu, \rho \text{ and } \theta.$$  

The pressure difference across the jet sheet $(P_a - P_s)$ at an angular position $\theta$, may therefore be related non-dimensionally to these parameters as follows:

$$\frac{(P_a - P_s)}{(P_T - P_a)} = f\left[\theta, \frac{t}{R}, \left(\frac{(P_T - P_a)R^2}{\rho \nu^2}\right)^{1/2}\right] \tag{2.2}$$

At some distance from the slot we might expect the flow to become independent of the separate parameters $(P_T - P_a)$ and $t$ and depend only on their product $(P_T - P_a)t$ as long as suitable zero is chosen for $\theta$. Furthermore, for large
values of Reynolds number the flow will tend to become independent of viscosity so that

\[
\frac{(P_a-P_s)R}{(P_T-P_a)t} = f(\theta)
\]  

(2.3)

From equation (2.2), the angular position of separation \( \theta_{sep} \) can be expressed as follows:

\[
\theta_{sep} = f\left[\frac{t}{R}, \left\{ \frac{(P_T-P_a)Rt}{\rho \frac{1}{2}} \right\}^{1/2}\right]
\]  

(2.4)

If the position of separation is sufficiently far from the slot, \( \theta_{sep} \) depends only on \( R_e \),

\[
\theta_{sep} = f\left[\left\{ \frac{(P_T-P_a)Rt}{\rho \frac{1}{2}} \right\}^{1/2}\right]
\]  

(2.5)

At large Reynolds number \( \theta_{sep} \) with suitably chosen zero, tends to become constant. In particular, for small values of \( t/R \), \( \theta_{sep} \) measured from the slot is constant. Experimental results (Ref. 1) confirm the above statement and they show that for \( t/R \) values ranging from 0.02 to 0.04, \( \theta_{sep} = 240^\circ \).

2.4 GAP EFFECT

In 1962, Korbacher (Ref. 3) investigated gap effect on a curved wall jet by measuring the forces and pressure acting on a quadrant. He found that the coanda phenomenon was also effective when the deflection surface was separated from the nozzle by a wide gap open to the
atmospheric pressure. The experiments were carried out for nozzle pressure ratios up to and well above the critical. Gaps along the nozzle axis up to eight times the jet slot width (at $R = 2.5$ in.) have practically no effect on the component of the force in the direction normal to the nozzle axis. Maximum $v'$ (at any given $h'$) for which the jet was able to bridge the gap depended on the jet slot width. The larger the $t$, the smaller is the $v'$. He concluded that the effect of $h'$ on the static pressure distribution on the wall was small. These findings were confirmed by Benner's investigation (Ref.4) which was a continuation of the work reported by Korbacher.

Paranjpe (Ref. 5) recently studied the gap effects on velocity profiles, position of separation and static pressure distribution. With different gaps, he found that in a region close to the leading edge of the wall, the velocity profile and rate of jet growth and maximum velocity decay were different from and eventually approached that of no gap. The settling region where the type of flow changed from a free jet to a wall jet, was found to increase with the gap size. The flow in the outer layer was unaffected by the gap. The pressure difference across the jet initially increased with gap size but at larger angles, the pressure difference reduced more rapidly for larger gaps indicating earlier separation. The value of angular position of
separation ($\Theta_{sep.}$) decreased with an increase in gap size.

For a given $h$, the jet attached to and detached from the curved wall at different values of $v$, namely, $v_A$ and $v_D$ respectively. This is known as the hysteresis phenomenon. Paranjpe (Ref. 5) found that with an increase in $h$, the difference between $v_A$ and $v_D$ decreased and their values approached that of the approximate free jet boundary. Korbacher (Ref. 3) also made a note of the hysteresis phenomenon.
CHAPTER III

TEST FACILITIES

The apparatus is shown in Figures 1, 2 and 3. References to the letter code used in Fig. 1 are made in the description of the test facilities.

3.1 AIR SUPPLY AND GUIDING DUCT

Air was supplied by a type HS, Size 200 American Standard Centrifugal fan (A) with static pressure of 5 in. of water. This fan was driven by a 5 h.p., 1745 r.p.m. General Electric induction motor. A 30 in. long, wooden guiding duct (B) with a rectangular cross section was attached to the fan exit. A honeycomb flow straightener was placed in the guiding duct to reduce the turbulence level induced by the fan.

3.2 CONTRACTION DUCT AND NOZZLES

A wooden contraction duct (C) 30 in. long was placed after the guiding duct. A converging nozzle (D) made of brass was attached to the contraction duct. Nozzles used were 0.25 in., 0.125 in. and 0.0625 in. wide and each had 9 in. span. The contraction ratios for the 0.25 in. nozzle together with the duct were 62:1 in the direction of 0.25 in. width and 2.5:1 in the perpendicular direction.
3.3 WALLS AND TRAVERSING MECHANISM

Curved walls having radii 3 in., 6 in., and 9 in. and each consisting of a 9 in. long half cylinder made of smooth plexiglass were used.

A piece of 30 in. x 40 in x 0.25 in. plexiglass plate on the top and a combination of rolled steel plate and plexiglass plate at the bottom were used as end plates to obtain the two dimensional flow condition. The wall (E) was mounted perpendicular to the end plates with the 9 in. direction being parallel to the spanwise direction of the jet slot.

The mechanism used for moving the wall to the required gap position, was capable of moving the wall both parallel and perpendicular to the jet. In both the directions, distances could be measured to an accuracy of 0.005 inch.

The traversing mechanism was provided with levelling screws to ensure correct alignment with the nozzle exit.

3.4 PROBING EQUIPMENT

A flattened stainless steel hypodermic tube with an opening of 0.005 in. x 0.060 in. was used to measure the total pressure in the jet. The probe was mounted on a traversing mechanism which moved the probe with an accuracy of 0.001 inch. An inclined manometer with an accuracy of
0.001 in. of water was utilised for pressure measurements.
CHAPTER IV

EXPERIMENTS

For each nozzle, the two dimensionality of the jet flow was checked by probing the jet at different spanwise locations. No significant changes in the velocity distributions were noted.

Throughout the experiment, the jet velocity at the nozzle exit was kept constant (145 ft./sec.). The Reynolds number ranged from $2.256 \times 10^4$ to $7.781 \times 10^4$.

With each nozzle-curved wall combination, the hysteresis phenomenon and wall jet separation were investigated.

4.1 THE HYSTERESIS PHENOMENON

For any gap $h'$, when the curved surface was moved away from the jet ($v'$ increased), at a particular value of $v'$ (say $v'_D$), the jet sheet detached from the surface. But when the curved surface was brought back ($v'$ reduced), the jet did not attach to the surface at $v'_D$ but attached at a lower value of $v'$, namely, $v'_A$ ($v'_A < v'_D$). This was because the jet had a tendency to maintain the detached or attached flow configuration until sufficiently affected by the movement of the curved surface. Further, both the attachment and detachment processes were rather abrupt in nature,
the detachment being somewhat less sudden than the attachment. \( v'_D \) and \( v'_A \) were determined by keeping the total pressure probe at a suitable distance from the nozzle and curved wall. At different values of \( h' \), these "attached" and "detached" positions were noted and "attached line" and "detached line" were plotted. This information (Fig. 4) was also useful for determining the range of gap sizes for other experiments.

4.2 VISUALIZATION OF FLOW SEPARATION

In order to determine the angular position of separation (\( \Theta_{\text{sep.}} \)), a well proportioned mixture of lamp black and kerosene was applied to the curved surface of the wall (Fig. 5). In the attached flow region, the motion of lamp black particles was influenced by two factors, namely, the jet flow and pull of gravity. In the region after the flow separation, the lamp black particles were not affected by the jet flow and hence the particle traces were vertical (Fig. 6). Following the flow direction, the location of the first vertical trace gave the position of jet separation from the wall.

The values of \( \Theta_{\text{sep.}} \) were determined for the curved wall jet with different values of \( v \) keeping \( h \) constant. This was done for three or more different values of \( h \) for each nozzle-curved wall combination.
CHAPTER V

EXPERIMENTAL RESULTS

5.1 THE HYSTERESIS PHENOMENON

Figures 4(a,b,c) show the variation of the "attached" and "detached" positions with $h'$ for 0.0625 in., 0.125 in. and 0.25 in. nozzle respectively ($R$ being the same) while Fig. 4(c,d,e) are respectively for 3 in., 6 in. and 9 in. curved wall ($t$ being the same). The approximate free jet boundary is also shown in Fig. 4. It is seen that the difference between the values of $v'$ for "detached" and "attached" positions, $m'$, first decreases slowly and then rapidly as $h'$ increases in all cases. It is interesting to note that the three lines come closer together as $h'$ is increased.

Further, it was observed during the experiments that for large values of $h'$, the deflection of the jet by means of the curved surface was not very stable. This may be explained by the fact that the value of $m'$ was small. This indicates that for a given nozzle-curved wall combination there is a maximum allowable value of $h'$ denoted by $h'_{\text{max}}$. The $h'_{\text{max}}$, as seen from Fig. 4 increases with a decrease in $t$ (keeping $R$ constant) and increases with an increase in $R$ (keeping $t$ constant). This is also shown in
Fig. 7. We see that \( h'_{\text{max}} \) is proportional to \( \frac{R}{t} \). This relationship was also intuitively expected from the simple theory which predicts that \( Cp = \frac{1}{R} \). Since \( h'_{\text{max}} \) is proportional to \( R' \), \( h_{\text{max}} \) is proportional to \( R \).

It is seen that the results obtained with different combinations of \( R \) and \( t \) agree with those obtained by Paranjpe (Ref. 5) qualitatively.

Figure 8 shows the variation of \( v_D \) with \( (Rt)^{1/2} \) for different \( h \). It is seen that as \( (Rt)^{1/2} \) increases, \( v_D \) also increases. At a given value of \( (Rt)^{1/2} \), it is noted that \( v_D \) increases with a decrease in \( t \) or an increase in \( R \). Further, it is seen that as \( t \) tends to zero, the constant \( t \)-plot tends to the ordinate. Also as \( R \) tends to zero, the constant \( R \)-plot tends to the origin. Thus for a wall of zero radius, \( v_D \) is zero. Hence the constant \( t \)-plots are extrapolated to pass through the origin. The constant \( R \)-line can be extrapolated to get the limiting value of \( t \) above which the jet will remain detached, i.e., \( v_D = 0 \).

Figure 9 is a dimensional plot between \( v_A \) and \( (Rt)^{1/2} \). It is seen that this plot is similar in nature to that of Fig. 8. However, the effect of \( h \) on \( v_A \) is greater than that on \( v_D \).

Plots in Fig. 10 show the "detached" positions for
different values of $h'$ and $R'$. It is seen that $v'_D$ increases with $R'$ and the dependance of $v'_D$ on $h'$ is very weak. Using the statistical method of linear regression the best line to fit the experimental data was drawn (correlation coefficient = 0.9932) and the following empirical relation was obtained:

$$v'_D = 0.061 (R')^{1.312}$$

For the "attached" positions, similar trends are obtained as given in Fig. 11. However, in this case, the effect of $h'$ is more pronounced than the "detached" case. The empirical relation could be expressed as:

$$v'_A = C(R')^n$$

where the values of the constants $C$ and $n$ depend on $h'$ (see Fig. 11 b).

5.2 SEPARATION

Had the curved surface been a full cylinder, separation would have been between $200^\circ$ and $220^\circ$, for zero gap and the Reynolds number range used (Ref. 2). But a half cylindrical surface perhaps being more useful for practical applications, was selected. For no gap, $\Theta_{sep}$ was between $125^\circ$ and $175^\circ$ depending on Re as shown in Fig. 12. It is noted that $\Theta_{sep}$ initially increases with an increase in Re but remains a constant at high Reynolds number. This is in agreement in principle with Fekete's result (Ref. 2). However, we notice a definite trend depending on $R$. An
improvement is obtained by plotting $\theta_{\text{sep.}}$ Vs. $\frac{Re}{R'}$ (Fig. 13).

Figure 14 shows $\theta_{\text{sep.}}$ Vs. $v'$ for different $h'$, $t$ and $R$. It is seen that a gap reduces $\theta_{\text{sep.}}$, reduction becoming appreciable as $v'$ tends to $v'_D$. It is evident that $\theta_{\text{sep.}}$ depends both on $h'$ and $v'$, larger the value of $h'$ and $v'$, smaller the angle $\theta_{\text{sep.}}$.

Further, when the curves in Fig. 14 are extrapolated to intercept the abscissa, the values of $v'$ obtained are very close to the corresponding $v'_D$. This brings out the point that detachment is the limiting case of separation.

The effect of $v'$ on the reduction of $\theta_{\text{sep.}}$ is more pronounced than that of $h'$. Therefore, in the following discussion of $\theta_{\text{sep.}}$ results, only the $h' = 0$ lines in the plots of Fig. 14 are considered.

Considering the rate of decrease of $\theta_{\text{sep.}}$ with $v'$, we note that it increases with a decrease in $R$ ($t$ kept constant) and an increase in $t$ ($R$ kept constant). This can be explained by the earlier detachment.

The variation of $\theta_{\text{sep.}}$ with $\frac{Re}{R'}$ for different $\frac{v}{v'_D}$ is shown in Fig. 15. The experimental mean lines from Fig. 13 and Fig. 15 are shown together in Fig. 16 from which we see that even with different gaps, the effect of $\frac{Re}{R}$ on $\theta_{\text{sep.}}$ is almost the same.
CHAPTER VI

CONCLUSIONS

6.1 THE HYSTERESIS PHENOMENON

1. With an increase in $h'$, the "attached line", "detached line" and approximate free jet boundary come closer together and the jet deflection by means of a curved surface becomes less stable.

2. $h_{\text{max}}$ is proportional to $R$.

3. For any given radius, there is a limiting value of $t$ above which the jet will remain detached.

4. $v_D'$ or $v_A'$ can be expressed as:

$$v_D' \text{ or } v_A' = C(R')^n$$

The constant "C" and index "n" do not change appreciably in the case of $v_D'$ and the relation is:

$$v_D' = 0.061(R')^{1.312}.$$ 

6.2 SEPARATION

1. An increase in gap reduces $\Theta_{\text{sep.}}$, reduction becoming appreciable as $v'$ approaches $v_D'$.

2. $v'$ has more effect on $\Theta_{\text{sep.}}$ than $h'$.

3. The rate of decrease of $\Theta_{\text{sep.}}$ with $v'$ for constant $h'$ increases with a decrease in $R$ ($t$ kept constant) and an increase in $t$ ($R$ kept constant).

4. A plot of $\Theta_{\text{sep.}}$ Vs. $\frac{Re}{H'}$ is better than that of $\Theta_{\text{sep.}}$ Vs. $Re$. 

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5. $Q_{\text{sep.}}$ initially increases with $\frac{Re}{R'}$ but remains a constant at high $\frac{Re}{R'}$.

6. Even with different gaps, the effect of $\frac{Re}{R'}$ on $Q_{\text{sep.}}$ is almost the same.
REFERENCES


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Fig. 2 SKETCH OF TEST REGION
Fig. 3 VIEW OF EXPERIMENTAL ARRANGEMENT
Fig. 4a HYSTERESIS PLOT
(R=3 in, t = 0.0625 in.)
Fig. 4b  HYSTERESIS PLOT  (R = 3 in., t = 0.125 in.)
Fig. 4d  HYSTERESIS PLOT  (R=6 in., t=0.25 in)
Fig. 4.e HYSTERESIS PLOT (R= 9 in., t= 0.25)

- Approximate Free Jet Boundary
- Attached Line
- Detached Line

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Fig. 5 VISUALIZATION OF FLOW SEPARATION
Fig. 6 SKETCH OF LAMP BLACK TRACES ON CURVED SURFACE
Fig. 7 PLOT OF $h'_{\text{max}}$ VS. $R'$. 

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Fig. 8a  DIMENSIONAL PLOT OF DETACHED POSITIONS

$V_D$ VS. $(Rt)^{1/2}$

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Fig. 8b DIMENSIONAL PLOT OF DETACHED
POSITIONS $v_D$ VS. $(Rt)^{1/2}$

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Fig. 9a DIMENSIONAL PLOT OF ATTACHED POSITIONS

$v_A$ vs. $(Rt)^{1/2}$
Fig. 9b  DIMENSIONAL PLOT OF ATTACHED POSITIONS $\gamma_A$ VS. $\sqrt{R_t}$
Fig. 10a NON DIMENSIONAL PLOT OF DETACHED POSITIONS ($v'_D$ VS. $R'$)

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Fig. 10b  NON-DIMENSIONAL PLOT OF DETACHED POSITIONS

\( v'_D = 0.061(R')^{1.312} \)

\( h'(\text{in}) = 12 8 4 2 0 \)

\( R' \) (in)

\( (\text{in}) \)

\( \bigcirc \text{ 3 1/4} \)

\( \square 6 1/4 \)

\( \diamond 9 1/4 \)

\( \triangle 3 1/8 \)

\( \triangle 6 1/8 \)

\( \downarrow 9 1/8 \)

\( \downarrow 3 1/16 \)

\( \downarrow 6 1/16 \)

\( \downarrow 9 1/16 \)

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Fig. IIa NON DIMENSIONAL PLOT OF ATTACHED POSITIONS
\( v'_A \) VS. R'
Fig. IIb NON-DIMENSIONAL PLOT OF ATTACHED POSITIONS

($v_A'$ VS. $R'$)

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Fig. 12 VARIATION OF θ_{sep} WITH Re FOR NO GAP
Fig. 14a  PLOTS OF $\theta_{\text{sep.}}$ VS. $v'$ FOR DIFFERENT $h'$
($R = 3 \text{ in}, t = 0.0625\text{ in}$)
Fig. 14b PLOTS OF $\theta_{sep.}$ VS. $v'$ FOR DIFFERENT $h'$

$(R = 3 \text{ in.}, t = 0.125 \text{ in.})$
Fig. 14c PLOT OF $\theta_{sep.}$ VS. $V'$ FOR DIFFERENT $h'$
($R = 3$ in., $t = 0.25$ in)
Fig. 14d PLOT OF θsep. VS. v' FOR DIFFERENT h'
(R=6 in., t=0.25 in)
Fig. 14e PLOTS OF $\theta_{sep}$ VS. $v'$ FOR DIFFERENT $h'$

(R = 9 in., $t = 0.25$ in.)
Fig. 15a  PLOT OF $\theta_{\text{sep.}}$ VS. $\frac{Re}{R'}$ FOR DIFFERENT $\frac{V}{V_D}$
Fig. 15b PLOT OF $\theta_{sep}$ VS. $R_e/R_f$ FOR DIFFERENT $V_d$
Fig. 16 EXPERIMENTAL MEAN LINES FOR DIFFERENT $\frac{R_e}{R}$ ($\Theta_{sep}$ vs. $\frac{R_e}{R}$)
APPENDIX

DIMENSIONAL ANALYSIS

For the present investigation, it is assumed that the following relation is true:

\[ Q_{\text{Sep.}} = f\left( (P_T - P_a), \rho, \nu, t, R, h, v \right) \]

In the M,L,T system of units, the dimensional matrix for the parameters is:

\[
\begin{bmatrix}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
Q_{\text{Sep.}} & R & h & v & (P_T - P_a) & \rho & t \\
M & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
L & 0 & 2 & 1 & 1 & 1 & -1 & -3 & 1 \\
T & 0 & -1 & 0 & 0 & 0 & -2 & 0 & 0
\end{bmatrix}
\]

It is apparent that the rank (r) of the matrix is three (3) and since there are eight (8) variables, the number of dimensionless groups is 8-3 = 5.

Taking \((P_T - P_a), \rho, t\) as the repeating variables, the dimensionless groups can be expressed as:

\[
\begin{align*}
\Pi_1 &= Q_{\text{Sep.}} \\
\Pi_2 &= (P_T - P_a)^x_1 (\rho)^y_1 (t)^z_1 \\
\Pi_3 &= (P_T - P_a)^x_2 (\rho)^y_2 (t)^z_2 R \\
\Pi_4 &= (P_T - P_a)^x_3 (\rho)^y_3 (t)^z_3 h \\
\Pi_5 &= (P_T - P_a)^x_4 (\rho)^y_4 (t)^z_4 v
\end{align*}
\]
Further the dimensionless groups are:

\[ \Pi_1 = \theta_{\text{Sep.}} \]
\[ \Pi_2 = \left[ \frac{(P_T - P_a)t^2}{\rho \nu} \right]^{-\frac{1}{3}} \]
\[ \Pi_3 = \frac{R}{t} \]
\[ \Pi_4 = \frac{h}{t} \]
\[ \Pi_5 = \frac{v}{t} \]

Dividing \( \Pi_2 \) by \( (\Pi_3)^{\frac{2}{3}} \), we get the dimensionless group as:

\[ \Pi_5 = \frac{\Pi_2}{(\Pi_3)^{\frac{2}{3}}} \]
\[ = \left[ \frac{(P_T - P_a)Rt}{\rho \nu} \right]^{-\frac{1}{3}} \]

Hence the relationship can be written as:

\[ F \left[ \theta_{\text{Sep.}}, \left\{ \frac{(P_T - P_a)Rt}{\rho \nu} \right\}^{-\frac{1}{3}}, \frac{R}{t}, \frac{h}{t}, \frac{v}{t} \right] = 0 \]
VITA AUCTORIS

1938  Born at Admabad, India on August 20.

1955  Completed high school education at Model High School, Jabalpur, India.

1957  Completed Intermediate Science Course at Mahakoshal Mahavidyalaya, Jabalpur, India.

1961  Received the Degree of Bachelor of Engineering (Honours) in Mechanical Engineering from Government Engineering College, Jabalpur, India.

1962  Finished the course requirements for Master of Engineering Degree in Mechanical Engineering at Roorkee University, Roorkee, India. Joined the engineering staff of M/S Heavy Engineering Corporation Ltd., Ranchi, India.

1964  Received the Degree of Master of Engineering in Mechanical Engineering at Roorkee University, Roorkee, India.

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