APPENDIX

The derivation of the equation for Reynolds Number for use in the sizing of control valves for non-turbulent flow (laminar and transitional)

The role of $F_d$ and $C_{VRTL}$ in calculating $R_{ev}$ for control valves.

The definition of the valve style modifier $F_d$, can be found in IEC std. 60534-2-1. In Reynolds Number the characteristic dimension “$J$” for control valves is the hydraulic mean diameter $d_H$.

$$d_H = 4 \times \text{effective area of the conduit / the wetted perimeter}.$$  

For a circular pipe or orifice with no restrictions or irregularities $d_H = \text{the pipe or orifice diameter}$. $F_d = d_H/d_e$ where $d_H$ = the hydraulic mean diameter of the controlling orifice (valve trim) and $d_e$ = the equivalent circular diameter for the valve trim.

For a single stage, single path trim the diameter of the vena contracta $d_{VC}$ is considered to be the same as $d_e$ making $F_d = d_H/d_{VC}$.

The rated $C_V$ of a control valve is:

$$C_{VR} = 4.625 \times 10^4 d_{VC}^2 \left(K_v K_{ap} \right) \frac{1}{F_L}$$

$d_e = \text{metres} \quad C_{VR} = \text{USGPM} \quad d_{VC}^2 K_v = d_{VC}^2 \text{ giving}$

$$d_{VC} = 4.65 \times 10^{-3} \sqrt{C_{VR} F_L} \frac{1}{\sqrt{K_v K_{ap}}}$$

$C_{VR}$ is the rated $C_V$ for a valve to pass the required flow, but in the turbulent regime. As explained earlier an estimate must be made at this stage of the size of valve required to pass the specified flow but in the non-turbulent regime. $C_{VR}$ is increased by a factor somewhere between 35% and 150% depending on the viscosity of the fluid. A valve is then selected with a rated $C_V$ nearest to this inflated $C_{VR}$. The selected rated $C_V$ is identified as $C_{VR L}$.

The vena contracta for this larger valve is:

$$d_{VC} = 4.65 \times 10^{-3} \sqrt{C_{VR L} F_L}$$

The product of the velocity and approach coefficients may be accepted as approximately unity.

To obtain the characteristic dimension $J$ (hydraulic mean diameter) in control valve terminology:

$$J = d_{VC} F_v = 4.65 \times 10^{-3} F_d \sqrt{C_{VR L} F_L}$$

In reviewing the technical literature it is found that various authors indicate that $1/\sqrt{K_v K_{ap}}$ has a minimal effect on $d_{VC} F_d$. It therefore been omitted.

The fundamental equation for Reynolds Number is:

$$R_{ev} = \frac{v J}{v}$$

where $v = \text{the velocity at the vena contracta} \quad v_{vc} \quad \text{m/sec}$

$J = \text{characteristic dimension} \quad d_{VC} F_d \quad \text{m}$

$v = \text{coef. of kinematic viscosity} \quad \text{m}^2/\text{sec}$

$Q = \text{volumetric flow} \quad \text{m}^3/\text{sec}$

$$v_{vc} = \frac{Q}{\pi d_{VC}^2} = 1.273 \frac{Q}{d_{VC}^2}$$
\[ R_{ev} = \frac{1.273.Q}{u.d_{VC}^2}.F_d = \frac{1.273.Q.F_d}{u} \times \frac{1}{4.65 \times 10^{-3} \sqrt{C_{VRTL}.F_L}} \]

\[ R_{ev} = \frac{273.76.Q.F_d}{u \sqrt{C_{VRTL}.F_L}} \]  \( Q = \text{m}^3/\text{sec}, \ C_{VRTL} = \text{USGPM}, \ u = \text{m}^2/\text{sec} \)

\[ R_{ev} = \frac{0.076.Q.F_d}{u \sqrt{C_{VRTL}.F_L}} \]  \( Q = \text{m}^3/\text{hr}, \ C_{VRTL} = \text{USGPM}, \ u = \text{m}^2/\text{sec} \)

\[ R_{ev} = \frac{76,000.Q.F_d}{u \sqrt{C_{VRTL}.F_L}} \]  \( Q = \text{m}^3/\text{hr}, \ C_{VRTL} = \text{USGPM}, \ u = \text{centistokes} \)

\( \text{centistokes} = \text{m}^2/\text{sec} \times 10^{-6} \)  \( \ast \) This is equation (A1) in IEC 60534-2-1 but omitting the bracket holding the velocity of approach term

Approximate values of K may be calculated from:

for standard trims where \( \frac{C_v}{d_i^2} \geq 0.016 \)  \( K = 2.14 \times 10^{-3} \left( \frac{C_v}{d_i^2} \right)^2 \)

for reduced size trims where \( \frac{C_v}{d_i^2} < 0.016 \geq 0.001 \)  \( K = 1 + \left[ 1.384 \times 10^{1.36} \left( \frac{C_v}{d_i^2} \right) \right] \)

when \( \frac{C_v}{d_i^2} < 0.001 \)  \( K = 1 \) constant

Values of K (turbulent) calculated from these equations may differ slightly from the turbulent K values indicated in figures 7 and 8 which are considered to be the more realistic.

For high capacity valves where \( \frac{C_v}{d_i^2} > 0.047 \)  \( K \) (turbulent) as calculated from

the equation \( \left( \frac{C_v}{d_i^2} \right) = \frac{2.14 \times 10^{-3} \ K}{K} \) will result in values less than 1. This initially seems strange since K is an indication of a valve’s resistance to flow so it is reasonable to expect its value to be in excess of 1. The low value is due to these valves having very high velocity of approach factors \( K_{ap} \) and very low pressure recovery factors \( F_L \).
Worked example (1)

Viscous liquid
\[ \nu = 162 \text{ centistokes} \]
\[ Q = 17 \text{ m}^3/\text{hr} \]
\[ \Delta p = 25 \text{ kPa} \]
\[ G = 0.92 \]
\[ CV = \text{USGPM} \]

Valve style selected – globe single seat V-port  \( F_d = 0.48 \quad F_L = 0.9 \)

Calculate \( C_{VT} \) for turbulent flow:
\[
Q = 8.65 \times 10^{-2} \cdot C_{VT} \sqrt{\frac{\Delta p}{G}} \\
17 = 8.65 \times 10^{-2} \cdot C_{VT} \sqrt{\frac{25}{0.92}} \\
C_{VT} = 37.7
\]

Increase \( C_{VT} \) by 90% = 71.6 which is an estimate of the rated \( C_V \) required for non-turbulent flow. Select a valve having the nearest rated \( C_V \) equal to or greater than 71.6.

This is a 75mm valve with a rated \( C_{VRTL} = 120 \).

To arrive at the rated \( C_V \) of the valve required for turbulent flow, increase \( C_{VT} \) by 20% giving 45. This suggests a 50mm valve with \( C_{VRT} = 50 \).

\[
\frac{C_{VRT}}{d_i^2} = \frac{50}{2500} = 0.020
\]

This is required for reading the values of \( K_L \) and \( f \) from the tables. The value of \( \text{Rev} \) is also required:
\[
\text{Rev} = \frac{76,000 \times Q \times F_d}{\nu \sqrt{C_{VRTL} \times F_L}}
\]
\[
\text{Rev} = \frac{76,000 \times 17 \times 0.48}{162 \times \sqrt{120 \times 0.9}} = 368
\]

From fig 3. \( K_L \) has the same value as the loss coefficient for turbulent flow \( K = 5.35 \)

From fig 5. \( f = 0.403 \text{Rev}^{0.084} = 0.403 \times 368^{0.084} = 0.660 \)

\[
F_R \sqrt{\frac{K}{K_L}} \times f \times \left( \frac{1}{F_i} \right) = \frac{5.35}{5.35} \times 0.660 = 0.660 \text{ for } F_L = 1, \text{ or } = 0.733 \text{ for } F_L = 0.90
\]

The \( CV \) of the valve require to pass the require flow under non-turbulent conditions is
\[
CV_L = \frac{37.7}{0.660} = 57.12, \text{ or } \frac{37.7}{0.733} = 51.43
\]

This compares favourably with the \( C_{VRTL} \) of the chosen 75mm valve = 120
If, in some cases, the \( C_{VRTL} \) indicates a valve greater than the one selected at the beginning of the procedure, the calculation must be repeated with \( C_{VT} \) increased by more than 90%.

**Worked example (2):**

Highly viscous liquid

\[
\nu = 1,100 \text{ centistokes} \\
Q = 17 \text{ m}^3/\text{hr} \\
\Delta p = 25 \text{ kPa} \\
G = 0.92 \\
C_V = \text{USGPM}
\]

Valve style selected – globe single seat V-port \( F_d = 0.48 \quad F_L = 0.9 \)

Calculate \( C_{VT} \) for turbulent flow:

\[
Q = 8.65 \times 10^{-2} \cdot C_{VT} \sqrt[3]{\frac{\Delta p}{G}}
\]

\[
17 = 8.65 \times 10^{-2} \cdot C_{VT} \sqrt[3]{\frac{25}{0.92}}
\]

\[
C_{VT} = 37.7
\]

Increase \( C_{VT} \) by 120\% = 83 which is an estimate of the rated \( C_V \) required for non-turbulent flow. Select a valve having the nearest rated \( C_V \) equal to or greater than 83.

This is a 75mm valve with a rated \( C_{VRTL} = 120 \).

To arrive at the rated \( C_V \) of the valve required for turbulent flow, increase \( C_{VT} \) by 20\% giving 45. This suggests a 50mm valve with \( C_{VRT} = 50 \).

\[
\frac{C_{VRT}}{d_1^2} = \frac{50}{2.500} = 0.020
\]

This is required for reading the values of \( K_L \) and \( f \) from the tables. The value of \( \text{Rev} \) is also required:

\[
\text{Rev} = \frac{76,000 \times Q \times F_L}{\nu \sqrt{C_{VRTL} \times F_L}}
\]

\[
\text{Rev} = \frac{76,000 \times 17 \times 0.48}{1100 \times \sqrt{120} \times 0.9} = 54
\]

From fig 3. \( K_L = 610 / \text{Rev} = 610 / 54 = 11.29 \quad K = 5.35 \)

From fig 4. \( f = 0.63 \)

\[
F_R = \sqrt{\frac{K}{K_L}} \times f \times \left( \frac{1}{F_L} \right) = \sqrt{\frac{5.35}{11.29}} \times 0.63 = 0.43 \text{ for } F_L = 1, \text{ or } = 0.48 \text{ for } F_L = 0.9
\]

The \( C_V \) of the valve require to pass the require flow under non-turbulent conditions is:
Given \[ CV_{VTL} = \frac{37.7}{0.43} = 87.67, \] or \[ CV_{VTL} = \frac{37.7}{0.48} = 78.54 \]

This compares favourably with the \( CV_{VTL} \) of the chosen 75mm valve = 120.

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**Fig 1** Reynolds Number Factor plotted against Reynolds Number - \( Re_a \)

- Curve (a) \( Cv/d_1^2 = 0.016 \)
- Curve (b) \( Cv/d_1^2 = 0.023 \)
- Curve (c) \( Cv/d_1^2 = 0.033 \)
- Curve (d) \( Cv/d_1^2 = 0.047 \)

\( Cv = \text{USGPM} \)

\( d_1 = \text{mm} \)

\( F_i \) in the calculation of the curves in Figs 1 & 2 is assigned the value of 1.0
Fig 1A Reynolds Number Factor plotted against Reynolds Number.

Curve (a) \( CV/d_1^2 = 0.016 \) \( F_r = 0.9 \)
Curve (b) \( CV/d_1^2 = 0.023 \) \( F_r = 0.8 \)
Curve (c) \( CV/d_1^2 = 0.033 \) \( F_r = 0.7 \)
Curve (d) \( CV/d_1^2 = 0.047 \) \( F_r = 0.6 \)

\( CV = \text{USGPM} \)
\( d_1 = \text{mm} \)
\( F_r \) in the calculation of the curves in Fig 1A is assigned the value for turbulent flow as indicated.
Fig 2  Reynolds Number Factor plotted against Reynolds Number - $Re_v$ for control valves with small $C_v$ - reduced trims.
# Equations

### Standard size trims

<table>
<thead>
<tr>
<th>$\frac{c_v}{d_i}$</th>
<th>$\text{Rev}$</th>
<th>$\text{Rev}$</th>
<th>$\text{Rev}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>1 - 60 $K_L = \frac{944}{\text{Rev}}$</td>
<td>60 - 250 $K_L = \frac{93.41}{\text{Rev}^{0.44}}$</td>
<td>$\geq 250$ $K_L = K = 8.50$</td>
</tr>
<tr>
<td>0.020</td>
<td>1 - 70 $K_L = \frac{610}{\text{Rev}}$</td>
<td>70 - 250 $K_L = \frac{44.00}{\text{Rev}^{0.38}}$</td>
<td>$\geq 250$ $K_L = K = 5.35$</td>
</tr>
<tr>
<td>0.033</td>
<td>1 - 100 $K_L = \frac{515}{\text{Rev}}$</td>
<td>100 - 500 $K_L = \frac{81.62}{\text{Rev}^{0.66}}$</td>
<td>$\geq 500$ $K_L = K = 1.96$</td>
</tr>
<tr>
<td>0.040</td>
<td>1 - 150 $K_L = \frac{468}{\text{Rev}}$</td>
<td>150 - 500 $K_L = \frac{105.14}{\text{Rev}^{0.70}}$</td>
<td>$\geq 500$ $K_L = K = 1.34$</td>
</tr>
<tr>
<td>0.047</td>
<td>1 - 250 $K_L = \frac{420}{\text{Rev}}$</td>
<td>250 - 1,000 $K_L = \frac{7.34}{\text{Rev}^{0.26}}$</td>
<td>$\geq 1,000$ $K_L = K = 1.16$</td>
</tr>
<tr>
<td>0.052</td>
<td>1 - 350 $K_L = \frac{386}{\text{Rev}}$</td>
<td>350 - 1,000 $K_L = \frac{7.00}{\text{Rev}^{0.32}}$</td>
<td>$\geq 1,000$ $K_L = K = 0.79$</td>
</tr>
<tr>
<td>0.065</td>
<td>1 - 400 $K_L = \frac{320}{\text{Rev}}$</td>
<td>400 - 1,500 $K_L = \frac{6.71}{\text{Rev}^{0.36}}$</td>
<td>$\geq 1,500$ $K_L = K = 0.50$</td>
</tr>
</tbody>
</table>

### Reduced size trims

<table>
<thead>
<tr>
<th>$\frac{c_v}{d_i}$</th>
<th>$\text{Rev}$</th>
<th>$\text{Rev}$</th>
<th>$\text{Rev}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1 - 250 $K_L = \frac{197}{\text{Rev}^{0.861}}$</td>
<td>250 - 700 $K_L = \frac{28.23}{\text{Rev}^{0.51}}$</td>
<td>$\geq 700$ $K_L = K = 1.0$</td>
</tr>
<tr>
<td>0.002</td>
<td>1 - 280 $K_L = \frac{269}{\text{Rev}^{0.861}}$</td>
<td>280 - 1,800 $K_L = \frac{19.77}{\text{Rev}^{0.40}}$</td>
<td>$\geq 1,800$ $K_L = K = 1.0$</td>
</tr>
<tr>
<td>0.003</td>
<td>1 - 300 $K_L = \frac{425}{\text{Rev}^{0.861}}$</td>
<td>300 - 1,850 $K_L = \frac{31.35}{\text{Rev}^{0.40}}$</td>
<td>$\geq 1,850$ $K_L = K = 1.5$</td>
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<tr>
<td>0.005</td>
<td>1 - 300 $K_L = \frac{638}{\text{Rev}^{0.861}}$</td>
<td>300 - 2,000 $K_L = \frac{60.73}{\text{Rev}^{0.35}}$</td>
<td>$\geq 2,000$ $K_L = K = 2.0$</td>
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<td>0.011</td>
<td>1 - 350 $K_L = \frac{1,054}{\text{Rev}^{0.861}}$</td>
<td>350 - 2,000 $K_L = \frac{40.35}{\text{Rev}^{0.30}}$</td>
<td>$\geq 2,000$ $K_L = K = 4.0$</td>
</tr>
</tbody>
</table>

Fig 3 Table of loss coefficients $K$ and $K_L$
Tabulated values for “f” the correction factor for $K_L$

### Standard size trims

<table>
<thead>
<tr>
<th>$\frac{C_v}{d_i^2}$</th>
<th>Rev</th>
<th>Laminar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>1 – 70</td>
<td>$f = 0.81$</td>
</tr>
<tr>
<td>0.020</td>
<td>1 – 70</td>
<td>$f = 0.63$</td>
</tr>
<tr>
<td>0.033</td>
<td>1 – 250</td>
<td>$f = 0.60$</td>
</tr>
<tr>
<td>0.040</td>
<td>1 – 300</td>
<td>$f = 0.57$</td>
</tr>
<tr>
<td>0.047</td>
<td>1 – 400</td>
<td>$f = 0.53$</td>
</tr>
<tr>
<td>0.052</td>
<td>1 – 600</td>
<td>$f = 0.48$</td>
</tr>
<tr>
<td>0.065</td>
<td>1 – 640</td>
<td>$f = 0.45$</td>
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<table>
<thead>
<tr>
<th>$\frac{C_v}{d_i^2}$</th>
<th>Rev</th>
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<tbody>
<tr>
<td>0.016</td>
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</tr>
<tr>
<td>0.020</td>
<td>$\geq 4,000$</td>
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</tr>
<tr>
<td>0.033</td>
<td>$\geq 4,000$</td>
<td>turbulent</td>
</tr>
<tr>
<td>0.040</td>
<td>$\geq 5,000$</td>
<td>turbulent</td>
</tr>
<tr>
<td>0.047</td>
<td>$\geq 5,500$</td>
<td>turbulent</td>
</tr>
<tr>
<td>0.052</td>
<td>$\geq 5,500$</td>
<td>turbulent</td>
</tr>
<tr>
<td>0.065</td>
<td>$\geq 5,500$</td>
<td>turbulent</td>
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<table>
<thead>
<tr>
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<tbody>
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<td>$&gt;70 – 111$</td>
<td>$f = 0.810$</td>
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<tr>
<td>0.020</td>
<td>$&gt;70 – 114$</td>
<td>$f = 0.630$</td>
</tr>
<tr>
<td>0.033</td>
<td>$&gt;250 – 262$</td>
<td>$f = 0.600$</td>
</tr>
<tr>
<td>0.040</td>
<td>$&gt;300 – 349$</td>
<td>$f = 0.570$</td>
</tr>
<tr>
<td>0.047</td>
<td>$&gt;400 – 1,800$</td>
<td>$f = 0.110 \text{Rev}^{0.260}$</td>
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<tr>
<td>0.052</td>
<td>$&gt;600 – 2,000$</td>
<td>$f = 0.084 \text{Rev}^{0.279}$</td>
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<tr>
<td>0.065</td>
<td>$&gt;640 – 2,400$</td>
<td>$f = 0.064 \text{Rev}^{0.301}$</td>
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<table>
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<tr>
<th>$\frac{C_v}{d_i^2}$</th>
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<td>0.016</td>
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<td>$&gt;114 – 600$</td>
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<td>$&gt;262 – 700$</td>
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<td>$f = 0.112 \text{Rev}^{0.244}$</td>
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<td>0.052</td>
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<td>$&gt;2,400 – 5,500$</td>
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<table>
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<td>$f = 0.337 \text{Rev}^{0.133}$</td>
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<td>0.020</td>
<td>$&gt;600 – 4,000$</td>
<td>$f = 0.210 \text{Rev}^{0.188}$</td>
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<td>0.033</td>
<td>$&gt;700 – 4,000$</td>
<td>$f = 0.103 \text{Rev}^{0.274}$</td>
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<tr>
<td>0.040</td>
<td>$&gt;1,000 – 5,000$</td>
<td>$f = 0.080 \text{Rev}^{0.296}$</td>
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</tbody>
</table>

Fig 4. Table of correction factors f for standard size trims.
Tabulated values for “f” the correction factor for $K_L$

Reduced size trims

$$\frac{c_y}{d_i^2}$$  |  Rev  |  Laminar  |
---|---|---|
0.011  |  1 – 90 | $f = 0.866 \text{Rev}^{0.027}$ |
0.005  |  1 -110 | $f = 0.711 \text{Rev}^{0.028}$ |
0.003  |  1 – 120 | $f = 0.661 \text{Rev}^{0.032}$ |
0.002  |  1 – 215 | $f = 0.537 \text{Rev}^{0.054}$ |
0.001  |  1 – 300 | $f = 0.395 \text{Rev}^{0.092}$ |

$$\frac{c_y}{d_i^2}$$  |  Rev  |  Transitional 2  |
---|---|---|
0.011  |  >90 – 350 | $f = 0.935$ |
0.005  |  >110 – 500 | $f = 0.910$ |
0.003  |  >120 – 550 | $f = 0.837$ |
0.002  |  >215 – 700 | $f = 0.725$ |
0.001  |  >300 – 1,000 | $f = 0.059$ |

$$\frac{c_y}{d_i^2}$$  |  Rev  |  Transitional 1  |  Rev  |  Turbulent  |
---|---|---|---|---|
0.011  |  >350 – 3,000 | $f = 0.779 \text{Rev}^{0.031}$ | $\geq 3,000$ | Turbulent |
0.005  |  >500 – 4,500 | $f = 0.714 \text{Rev}^{0.040}$ | $\geq 4,500$ | Turbulent |
0.003  |  >550 – 5,000 | $f = 0.512 \text{Rev}^{0.078}$ | $\geq 5,000$ | Turbulent |
0.002  |  >700 – 6,000 | $f = 0.312 \text{Rev}^{0.134}$ | $\geq 6,000$ | Turbulent |
0.001  |  >1,000 – 7,000 | $f = 0.152 \text{Rev}^{0.213}$ | $\geq 7,000$ | Turbulent |

Fig 5 Table of correction factor $f$ for reduced size trims
Fig 6. Variation of coefficient K with the valve capacity in relation to the valve size. - $Cv/ d_1^2$
Curve (a)  $\frac{Cv}{d_1^2} = 0.016$
Curve (b)  $\frac{Cv}{d_1^2} = 0.020$
Curve (c)  $\frac{Cv}{d_1^2} = 0.033$
Curve (d)  $\frac{Cv}{d_1^2} = 0.047$
Curve (e)  $\frac{Cv}{d_1^2} = 0.065$

$Cv$ = USGPM
$d_1$ = mm

Fig 7. Loss Coefficients plotted against Reynolds Number – $Re_v$. 
Curve (f) \( \frac{C_v}{d_1^2} = 0.011 \)  \( C_v = \text{USGPM} \)  \( d_1 = \text{mm} \)
Curve (g) \( \frac{C_v}{d_1^2} = 0.005 \)
Curve (h) \( \frac{C_v}{d_1^2} = 0.003 \)
Curve (i) \( \frac{C_v}{d_1^2} = 0.002 \)
Curve (j) \( \frac{C_v}{d_1^2} = 0.001 \)

Fig 8. Loss Coefficients plotted against Reynolds Number - \( \text{Re}_v \) for control valves with small \( C_v \)s – reduced trims.
Nomenclature

$C_v$ = valve flow coefficient – USGPM

$d_1$ = valve inlet diameter – mm

$d_{H}$ = hydraulic mean diameter – m

$d_S$ = valve trim effective diameter - mm

$f$ = $K_L$ correction factor

$F_P$ = piping geometry factor.

$F_R$ = Reynolds Number factor

$G$ = specific gravity

$K$ = valve turbulent loss coefficient

$K_L$ = valve non-turbulent loss coefficient

$I$ = characteristic dimension in Rev - m

$N$ = numerical constant

$p$ = pressure - kPa abs.

$\Delta p$ = pressure drop across valve - kPa

$Q$ = volumetric flow rate – $m^3$/hr

$v$ = velocity – m/sec

$\nu$ = kinematic viscosity – $m^2$/sec or centistokes

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