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Improve pressure drop calculations for saturated water lines

When saturated water flows through pipes and components, it flashes—thus increasing its specific volume and limiting the fluid flowrate. Due to these conditions, the calculation and design for piping associated with boilers and steam generation are very complicated. To avoid oversizing of pipes and components, improved equations can more accurately calculate the pressure drop for saturated water at high pressure.

Traditional method. The present way to design these lines involve iterative or graphic methods.[1–4] This approach is very time-consuming. Based on practical experience with power and nuclear plant projects, a new equation was effectively developed to calculate the flowrate of saturated water as a function of the pressure drop. It also includes the pipe resistance coefficient, saturation pressure, and the internal pipe diameter for critical and noncritical conditions.

New proposed equation. Most practical cases that must be resolved are related to $\Delta P/P_S \geq 0.2$. The new equation proposed is:

$$W = 280C_E D^2 \ln P_S \, (\Delta P/v_s K)^{0.5} \quad (1)$$

The coefficient, C_E, is taken from **FIG. 1.** It is referenced to P_S = 1,000 psia. In **FIG. 1,** $\Delta P/P_S$ is valid for saturated water pressure, P_S. This equation is similar to that existing for steam and gases.[6] From this equation, $W = 1{,}891YD^2(\Delta P/v_s K)^{0.5}$. For P_S = 1,000 psia and saturated water, it will be $W = 1{,}891C_E D^2 (\Delta P/v_s K)^{0.5}$. When P_S is corrected by $C_E 0.148 \ln P_S$, the results yield a new equation.

The results obtained from Eq. 1 are multiplied by the correction factors—*C1, C2* and *C3*—in these cases:

Case 1-C1. When there are critical conditions at the end of the pipe and $P_S \leq 100$ psia and $K \leq 100$, then apply *C1*.

$$C1 = 1.33/P_S^{0.06}$$

Case 2-C2. When there are noncritical conditions at the end of the pipe and $P_S \leq 200$ psia, then apply *C2*.

$$C2 = 0.82K^{0.04}$$

Case 3-C3. When there are noncritical conditions at the end of the pipe and $P_S > 200$ psia and $P_S \leq 400$ psia, then apply *C3*.

$$C3 = (1.61 + 0.001K)/P_S^{0.07}$$

In the rare cases when $\Delta P/P_S < 0.2$, apply *C1* for critical conditions at the end of the pipe and $C4 = 1.25/P_S^{0.03}$ for noncritical conditions and when $P_S \leq 500$ psia. The results of the new equation plus the defined corrections can provide values very similar to that obtained with the present calculation methods.

Critical conditions at the end of the pipe. Conditions do change. **FIGS. 2** and **3** illustrate conditions for P_S, critical pressure at the end of the pipe, P_{CR}, and the pipe resistance coefficient, *K*, from the point of the pipe where the flashing starts until the end of the pipe.

For selected *K* and P_S values, if the receiver pressure where the pipe ends, P_R, is ≥ than the corresponding P_{CR} value (**FIGS. 2** and **3**), then the flashed water enters into the receiver with the pressure $P_F = P_{CR}$; now, the flow is critical. Conversely, if $P_R > P_{CR}$, then the pressure at the end of the pipe is shown as $P_F = P_R$.

The total pressure drop (ΔP) can be estimated as $P_s - P_{CR}$ or $P_S - P_R$. The saturated water flow, *W*, is calculated applying Eq. 1.

Example: Heater drain line. As shown in **FIG. 4,** normally, the pipe upstream of the control valve is designed to ensure that the pressure at the valve entrance (point 1) equals the saturation pressure, P_S; thus, flashing of the water starts at this point. The point 1 to F will be discussed and it includes the control valve and the pipe run, 2-F, to calculate the passing flowrate equal or greater than the maximum required *W*. The starting data are *W*, P_S and P_R, and we must determine the valve capacity and the layout and pipe diameter of the run 2-F.

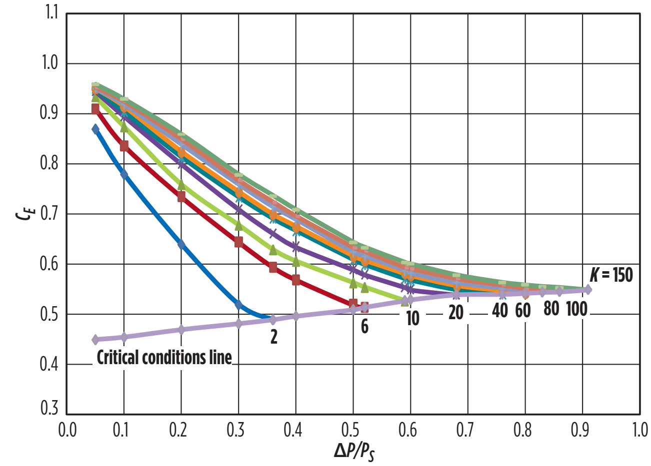

FIG. 1. Values for expansion coefficient for saturated water including pipe and components when P_s = 1,000 psia.

As a rule of thumb, if $P_R \leq 0.3\, P_S$, the design of 1-F is done so that $P_F = P_{CR} > P_R$. Conversely, if $P_R > 0.3P_S$, the design of 1-F is done so that $P_F = P_R$.

The calculation and design of the run 1-F should follow these steps:

Step 1. Calculate the maximum allowable pressure drop in the valve, ΔP_{vmax}, 100% open for the maximum required flow, W:[5]

$$\Delta P_{vmax} = 0.04 F_L^{\,2} P_S [1 + 7(P_S/3{,}206)^{0.5}]$$

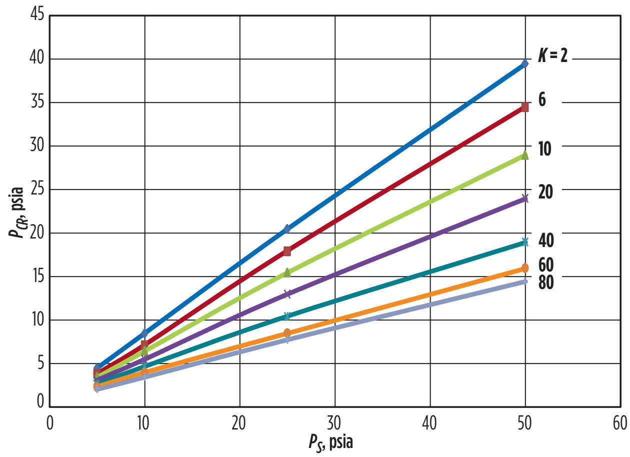

FIG. 2. Relationship between P_{CR}, K and P_s for the flow of saturated water through pipes and components.

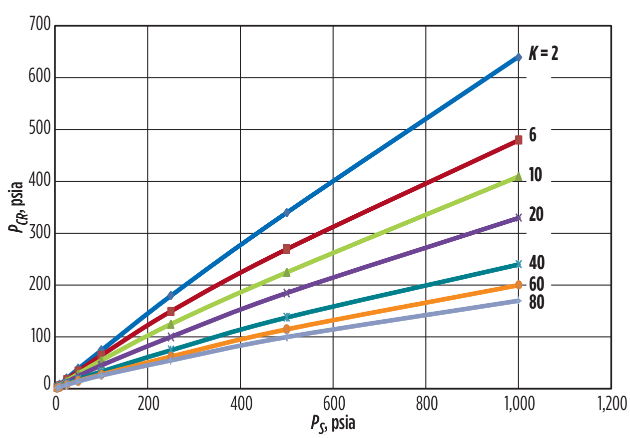

FIG. 3. Relationship between P_{CR}, K and P_s for the flow of saturated water through pipes and components.

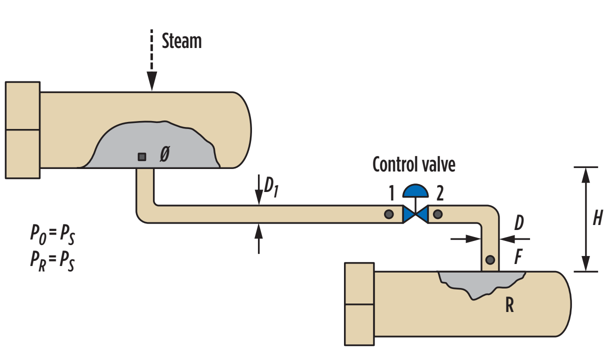

FIG. 4. Example of design pipe run with control valve to maximize the flowrate of saturated water.

This equation is represented in **FIG. 5. Note:** If $P_S - \Delta P_{vmax} \leq P_R$, then select a pressure drop in the valve where $\Delta P_v = 0.9\,(P_S - P_R)$ and hold the remaining 10%, or

$0.1(P_S - P_R)$ for the pressure drop in the pipe run 2-F. In this case, it will be $P_F = P_R$.

Step 2. Calculate the valve flow coefficient, C_v:

$$C_v = (W/63.3)(v_s/\Delta P_{vmax})^{0.5}$$

Step 3. Calculate the equivalent pipe resistance coefficient of the valve, referred to the run 2-F diameter, D:

$$K_v = 894 D^4/C_v^{\,2}$$

Step 4. With the new pipe diameter for the run 2-F and based on the pipe layout (straight run, number of elbows and receiver entrance), calculate the pipe resistance coefficient:[6]

$$K_{2F} = fL/D$$

Step 5. The total pipe resistance coefficient of the run 1-F will be $K = K_v + K_{2F}$. Check in **FIGS. 2** or **3** for K and P_S to confirm the value of P_{CR}. If $P_{CR} \geq P_R$, then pressure at the end of the pipe, point F, will be $P_F = P_{CR}$. If $P_{CR} < P_R$, then it will be $P_F = P_R$.

Step 6. Finally, use Eq. 1 and its corrections to calculate the flowrate, taking for $\Delta P = P_S - P_{CR}$ or $P_S - P_R$ according to the Step 5.

If the calculated flowrate is equal to or greater than the maximum required, the assumed D value is correct. If it is lower, try a larger value for D and repeat Steps 3 through 6.

Numerical example. Calculate the control valve and the pipe diameter of the run 2-F. Assume that the starting data are: $P_1 = P_S = 200$ psia; $v_s = 0.01839$ ft^3/lb; $P_R = 100$ psia; $F_L = 0.9$

Layout of the run 2-F: straight run = 10 ft; 3 standard elbow 90°; receiver entrance, $K = 1$

Maximum required flow = 200,000 lb/hr.

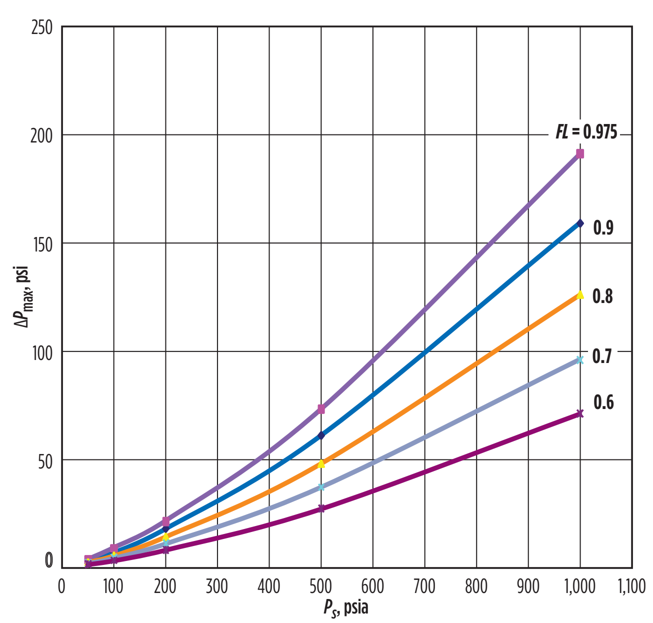

FIG. 5. Maximum allowable pressure drop through control valves for saturated water when the entrance pressure, $P_1 = P_s$.

Applying estimation steps and estimates:

1) $\Delta P_{vmax} = 0.04 \times 0.9^2 \times 200[1 + 7(200/3{,}206)^{0.5}] =$ 17.81 psi
2) $C_v = (200{,}000/63.3)(0.01839/17.81)^{0.5} = 101.53$

For a standard globe valve, the C_v may correspond to a 4-in. size valve.

3) Try for run 2-F with the diameter $D = 4$ in.; now, $K_v = 894 \times 4^4/101.53^2 = 22.2$
4) For $D = 4$ in. and turbulent flow, the estimate is:[6]

   $f = 0.016$ and every 90° standard elbow has $L/D = 30$, so K_{2F} will be:

   $K_{2F} = 1 + 0.016 \times 10 \times 12/4 + 0.016 \times 3 \times 30 = 2.92$
5) $K = 22.2 + 2.92 = 25.12$

Using **FIG. 3,** $P_S = 200$ psia and $K = 25.12$ is $P_{CR} = 77$ psia and $P_R = 100$ psia, so $P_F = P_R = 100$ psia and $\Delta P = P_S - P_R = 100$ psi

6) Use Eq. 1 to calculate the flowrate. First, obtain C_E from **FIG. 1.**

For $\Delta P/P_S = 100/200 = 0.5$ and $K = 25.12$, it is $C_E = 0.593$

$W = 280 \times 0.593 \times 4^2 \times \ln 200(100/0.01839 \times 25.12)^{0.5} = 207{,}095$ lb/h

As $P_S = 200$ psia, and there are no critical conditions, then the correction $C2$ will apply:

$C2 = 0.82 \times 25.12^{0.04} = 0.933$

The corrected flowrate will be: $W = 207{,}095 \times 0.933 = 193.190$ lb/h. This value is less than the 200,000 lb/h required.

Repeat steps 3 through 6 with $D = 5$ in.:

3) $K_v = 894 \times 5^4/101.53^2 = 54.2$
4) For $D = 5$ in. and turbulent flow is $f = 0.0152$ and K_{2F} is:

   $K_{2F} = 1 + 0.0152 \times 10 \times 12/5 + 0.0152 \times 3 \times 30 = 2.73$
5) $K = 54.2 + 2.73 = 56.93$. From **FIG. 3,** $P_{CR} = 55$ psia and $P_R = 100$ psia.

   Now, $P_F = P_R = 100$ psia and $\Delta P = 100$ psi.
6) $\Delta P/P_S = 0.5$ and $K = 56.93$. From **FIG. 1,** $C_E = 0.615$ and

   $W = 280 \times 0.615 \times 5^2 \times \ln 200(100/0.01839 \times 56.93)^{0.5} = 222{,}920$ lb/hr.

   Correcting with $C2 = 0.82 \times 56.93^{0.04} = 0.964$ is:

   $W = 222{,}920 \times 0.964 = 214{,}870$ lb/h > 200,000 lb/hr.

A 4-in. standard globe valve and a 5-in. pipe for the assumed layout of run 2-F is the right design to pass the maximum flowrate of 200,000 lb/hr of saturated water. HP

NOMENCLATURE/LITERATURE CITED

Nomenclature and literature cited available at HydrocarbonProcessing.com.

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