6.4 JET FIRES

The jet fire analysis in ALOHA is designed to address the thermal radiation hazards associated with gases and aerosols released from pressurized tanks and pipes which ignite before the vapors disperse downwind. Jet fires differ from flash fires in that they completely burn immediately upon release at the surface of a fuel-rich core. Jet fires differ from fireballs in that jet fires are associated with sustained releases, while fireballs are associated with an explosive tank rupture due to overpressurization.

The Jet Fire model in ALOHA can be applied to an upward vertical jet release: a pipe oriented vertically or a hole at the top of a tank. The method in ALOHA is based on an empirical solid flame model developed by Shell Research (Chamberlain 1987). Fuel released from the pipe or tank expands, mixes with air, and burns on its surface emitting intense thermal radiation that propagates outward. The thermal energy incident upon a distant target is a product of the emissivity of the flame surface, the geometric view factor, and the transmissivity of the atmosphere to thermal radiation.

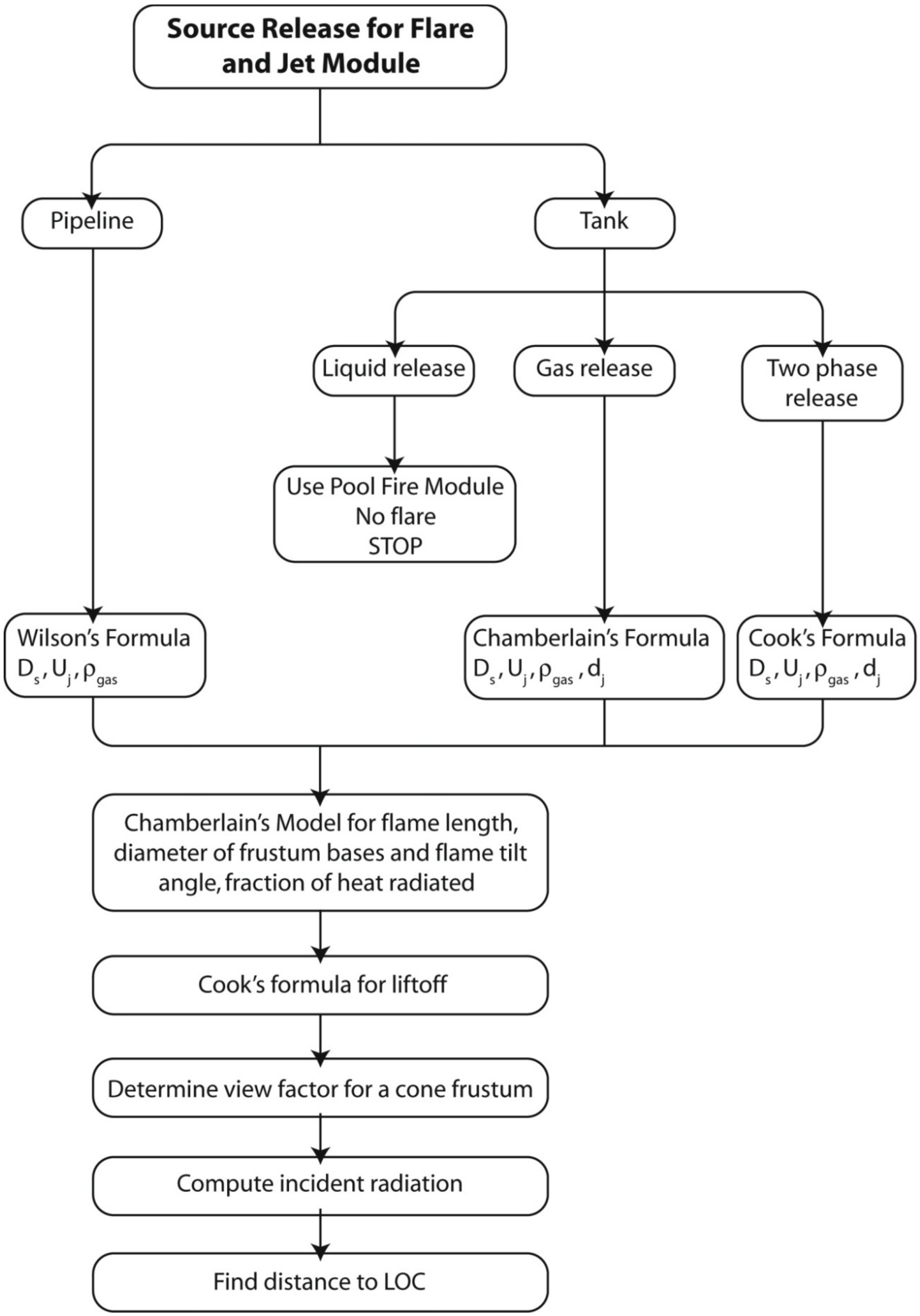

Figure 3. Source release for jet fire flowchart.

6.4.1 EMISSIVITY

From Cook et al (Cook, Bahrami, and Whitehouse 1990), the emissive power of the flame, *E*, is calculated as

$$E = \frac{f_{rad} Q \Delta h_c}{A},$$

where

Q is the mass discharge rate (kg s^{-1}),

Δh_c is the heat of combustion (J kg^{-1}), and

A is the surface area of the flame (m^2).

From Chamberlain (Chamberlain 1987), the fraction of heat radiated from the flame surface is

$$f_{rad} = 0.21 C_{MW} \exp(-0.00323 u_j) + 0.11.$$

Where C_{MW} is a correction factor introduced by Cook et al (Cook, Bahrami, and Whitehouse 1990) equal to unity if the molecular weight is less than 21 g mole^{-1}, the square root of the molecular weight divided by 21 if the molecular weight is between 21 g mole^{-1} and 60 g mole^{-1}, and equal to 1.69 if the molecular weight is greater than 60 g mole^{-1}.

The gas velocity in the expanding jet is

$$u_j = M_j \sqrt{\frac{\gamma_g R_c T_j}{W_{gk}}}$$

and

$$T_j = \frac{2T_s}{2 + \left(\gamma_g - 1\right) M_j^2},$$

where T_s is temperature inside vessel or at exit of pipe.

For unchoked flow, the Mach number of the expanded jet, M_j, is calculated by

$$M_j = \left[\frac{\left(1 + 2(\gamma_g - 1) F^2\right)^{\frac{1}{2}} - 1}{(\gamma_g - 1)} \right]^{\frac{1}{2}} \text{ and}$$

$$F = 3.6233 \cdot 10^{-5} \frac{Q}{d_o^2} \sqrt{\frac{T_s}{\gamma_g W_{gk}}},$$

where
d_o is the diameter of the orifice,
Q is the mass release rate,
γ_g is the ratio of specific heats,
W_{gk} is the molecular weight (kg mole^{-1}), and
R_c is the gas constant (8.3144 J K^{-1} mole^{-1}).

6.4.2 VIEW FACTOR

The flame surface is approximated as a frustum of a cone tilted by the wind.

The effective source diameter is the throat diameter of an imagined nozzle from which air at normal ambient density issues at the gas mass flow rate and exit velocity. The effective source diameter for a gas is

$$D_s = d_o \sqrt{\frac{\rho_j}{\rho_{air}}},$$

where
d_o is the diameter of the exit orifice, and
ρ_j is the density of the gas.

For choked flow the Mach number is

$$M_j = \sqrt{\frac{(\gamma_g + 1)\left(\frac{P_c}{P_o}\right)^{\frac{(\gamma_g - 1)}{\gamma_g}} - 2}{(\gamma_g + 1)}},$$

where
P_o is atmospheric pressure,
P_c is static pressure at the exit orifice, and

$$P_c = 3.6713 \frac{Q}{d_o^2} \sqrt{\frac{T_c}{\gamma_g W_{gk}}},$$

$$T_c = \frac{2T_s}{1+\gamma_g}$$

where T_s is the temperature inside the vessel or at the exit of the pipe.

The jet expands to atmospheric pressure at a plane downstream of the exit hole with the plane acting as a virtual source of diameter, d_j. Then,

$$D_s = d_j \sqrt{\frac{\rho_j}{\rho_{air}}} \text{ and}$$

$$d_j = \sqrt{\frac{4Q}{\pi u_j \rho_j}} = \sqrt{\frac{4Q}{\pi P_o M_j}\sqrt{\frac{R_c T_j}{\gamma_g W_{gk}}}} = \sqrt{3.6233 \cdot 10^{-5} \frac{Q}{M_j}\sqrt{\frac{T_j}{\gamma_g W_{gk}}}},$$

where u_j is the velocity of the gas in the expanded jet.

These formulas were modified slightly for the pipeline jet fire and two-phase release scenarios. ALOHA assumes that the gas expands adiabatically in the last 200 pipe diameters in the pipeline release. It exits at atmospheric pressure and therefore the effective source diameter, D_s for the choked option reduces to that for the unchocked option given earlier. For two-phase release, ALOHA uses a modification of the formula in Cook et al. (Cook, Bahrami, and Whitehouse 1990),

$$D_s = d_j \left(\frac{\rho_j \rho_v}{\rho_{air}^2}\right)^{1/4},$$

where ρ_v is the pure vapor density.

The modification of the Cook formula was necessary to insure that it would reduce to the proper algorithm when the two-phase case reduced to the pure gas scenario.

For a tilted jet, Kalghatgi (Kalghatgi 1983) showed in laboratory experiments that the flame length reduces as the jet is tilted into the wind. Chamberlain uses Kalghatgi's empirical fit equation to determine the flame length, L_B (Kalghatgi 1983) as

$$L_B = 105.4 D_s \left[1 - 6.07 \cdot 10^{-3} \left(\theta_j - 90\right)\right].$$

The flame length in still air is

$$L_{Bo} = \frac{L_B}{\left[0.51 \exp\left(-0.4v\right) + 0.49\right]\left[1 - 6.07 \cdot 10^{-3}\left(\theta_j - 90\right)\right]}.$$

The angle, α, between the orifice axis and the flame depends on the velocity ratio, is

$$R = \frac{V}{u_j},$$

where V is the wind speed.

If $R \le 0.05$, then

$$\alpha = \frac{8000R + \xi\left(L_{Bo}\right)\left(\theta_j - 90\right)\left(1 - \exp\left(-25.6R\right)\right)}{\xi\left(L_{Bo}\right)},$$

and if $R > 0.05$, then

$$\alpha = \frac{\left[1726\sqrt{R-0.026} + 134\xi\left(L_{Bo}\right)\left(\theta_j - 90\right)\left(1 - \exp\left(-25.6R\right)\right)\right]}{\xi\left(L_{Bo}\right)} \text{ and}$$

$$\xi\left(L_{Bo}\right) = L_{Bo}\left[\frac{g}{D_s^2 u_j^2}\right]^{\frac{1}{3}}.$$

The flame-lift off, b, is the distance along the axis of the cone, and is calculated as

$$b = 0.015L_B \text{ for aerosols, and } b = L_B\frac{\sin K\alpha}{\sin\alpha} \text{ for gases.}$$

K has been correlated with experimental data with a best fit of

$$K = 0.185e^{-20R} + 0.015.$$

The frustum length is given by the geometrical relationship between R_L, L_B, α and b, as

$$R_L = \sqrt{\left(L_B^2 + b^2\sin^2\alpha\right)} - b\cos\alpha.$$

There appears to be a difference in the formula for the width of the frustum base as it appears in Chamberlain's paper when compared to Lees (Lees 2001) presentation of Chamberlain's formula. Based on sample calculations, we determined to use the Chamberlain's version (Chamberlain p. 303) with the width of the frustum base., W_1, as

$$W_1 = D_s\left[13.5\exp\left(-6R\right) + 1.5\right]\left\{1 - \left[1 - \frac{1}{15}\left(\frac{\rho_a}{\rho_j}\right)^{\frac{1}{2}}\right]\exp\left(-70\xi\left(D_s\right)^{CR}\right)\right\},$$

where

$$C = 1000\exp\left(-100R\right) + 0.8$$

and the Richardson number, $\xi(D_s)$, based on D_s is

$$\xi(D_s) = \left(\frac{g}{D_s^2 u_j^2}\right)^{\frac{1}{3}} D_s .$$

The Chamberlain formula for the width at frustum tip, W_2, is

$$W_2 = L_B\left(0.18\exp(-1.5R) + 0.31\right)\left(1 - 0.47\exp(-25R)\right).$$

The surface area of the flame, *A*, is calculated as

$$A = \frac{\pi}{4}\left(W_1^2 + W_2^2\right) + \frac{\pi}{2}(W_1 + W_2)\left[R_L^2 + \left(\frac{W_2 - W_1}{2}\right)^2\right]^{\frac{1}{2}} .$$

The view factor F is defined by Sparrow and Cess (Sparrow and Cess 1978) as

$$dF_{A_j - dA_i} = \frac{dA_i}{A_j}\int_{A_j}\frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2},$$

where
A_j is the area of the radiating surface;
dA_i is the receiving element;
β_i is the angle between the normal to the receiving element and the line between the element and the radiating surface;
β_j is the angle between the normal to the radiating surface at a point and the line between that point and the receiving element; and
r is the distance between the point on the radiating surface and the receiving element.

For a radiating surface of area A_i and a receiving element of area dA_j, we can let
q' = incident radiation intensity per unit area, and
E' = emissive power per unit area,

so that

$$q' = \frac{q}{dA_i} = \frac{E \cdot F \cdot \tau}{dA_i} = \frac{E' \cdot A_j \cdot F \cdot \tau}{dA_i} = E' \cdot \left(\frac{A_j}{dA_i} \cdot F\right) \cdot \tau .$$

Thus, it is actually $\int_{A_j}\frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2}$ that we need to calculate.

We calculate this integral numerically by dividing the flame surface into 1800 "tiles" (40 radial divisions x 25 axial divisions of the conical surface, plus 400 tiles for each circular "cap"). The value of the integrand is calculated at the center of each tile, and those values are added to produce an estimate of the integral. This process is carried out for three orthogonal orientations of the receiving surface, producing view factors f_1, f_2, and f_3. The maximum view factor (over all orientations of the receiving surface) is then calculated as

$$f = \sqrt{f_1^{\,2} + f_2^{\,2} + f_3^{\,2}}\ .$$

(For a true view factor, the integral omits portions of the radiating surface where $\cos\beta_j$ <0. But since f_1, f_2, and f_3 are used to calculate the maximum view factor, portions where $\cos\beta_j$ <0 are not excluded.)

6.5 POOL FIRES

There are 3 release scenarios that can be coupled with the Pool Fire model: The user may choose to model a pool of constant area that is not associated with a tank release; the Pool Fire model can also be coupled with a model that estimates the pool formation dynamics when a tank of chemical is leaking; and the Pool Fire model is automatically applied to any fuel that pools during a BLEVE scenario. In all cases, the pool is assumed to be circular, uniformly thick, and on a level surface. The pool temperature is approximated as a constant and set to either the initial pool temperature or the initial tank temperature. A 200-meter diameter limit applies in all cases.

A solid flame model is used to calculate the thermal radiation from pool fires. The size of the pool can be set by the user, or ALOHA will calculate the dynamic area and volume from the release of a liquid from a tank. The flames rising from the pool form a tilted cylinder; the surface of the cylinder radiates thermal radiation. Burn rate, flame height, angle of tilt, and emission of radiation from the surface are based on empirical correlations.

The thermal energy incident upon distant target is the product of the thermal radiation energy flux at the surface of the flame, the geometric view factor, and the transmissivity of the atmosphere to thermal radiation.

6.5.1 EMISSIVITY

The average emissive power per unit area, *E*, of the cylinder surface is estimated using the approach of Moorhouse and Pritchard (Moorhouse and Pritchard 1982),

$$E = \frac{f_{rad}\Delta h_c \dot{m}}{\left(1 + 4\dfrac{h}{d}\right)},$$