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The Pool Fire Case for Pressure Relief: Radiation Exposure Limited by Fuel Supply

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Abstract

In design of pressure relief systems, a pool fire is one of the most typical relief cases. The first step in the fire relief calculation is determining the heat flux input from the fire and methods include the simple to the very complex, covering a myriad of factors and configurations. This paper illustrates one method where the heat input is limited by the fuel supply. This method complements one traditional method where the heat input is limited by the equipment exposed area. The scope of the paper is limited to the calculation of the heat release, and does not discuss the behavior of the fluid in subject equipment, the relief rate or relief device sizing.

1. Introduction

When modeling the pool fire case for engineering applications, such as fire relief determination, the situation may not fit one particular model so alternatives may be used.

The most widely used model is an empirical method from NFPA-API [2,6]. This is based on fire tests and is generally applicable for large tanks located at a grade susceptible to a pool fire and essentially full of liquid. The Appendix 5.2.1 provides a short summary.

If the assumptions used for the NFPA-API model do not apply, for example if the flame height is tall (e.g., greater than 25 feet or 30 feet depending on the standard used) [18], then other analytical models may be used, as outlined in the appendix.

But there may be a situation where equipment is located on a well-drained grade yet has a large surface area. For this case, the heat input may very well be limited by the amount of fuel that is burned. This presentation will outline one method to determine the amount of fuel and the heat release. The method is based on well research published data [1].

2. Radiation Exposure Limited by Fuel Supply Model

The model states that the radiant heat incident to the equipment is generated by the amount of fuel combusted in the fire. The primary assumption is that the pool fire is adjacent to the equipment and the amount of radiation absorbed by atmosphere is negligible ($\tau = 1.0$). The heat of combustion from the amount of fuel burned is radiated to the target. This model is useful if the fire is small or if the equipment has a very large exposed area. This model is compared with others in the appendix.

$$Q_I = Q_R F \tau = m_B H_C \eta F \tau \qquad \text{… Eq. (1)}$$

where : Q_I is the radiant heat to the target [Btu/hr]
Q_R is the radiant heat release [Btu/hr]
m_B is the fuel mass burn rate [lb/hr]
H_C is the fuel lower heating value [Btu/lb]
η is the fraction of total heat radiated
F is the radiation view factor or the fraction of incident radiation received by the target from the emitting surface per unit area
τ is the radiation transmissivity or the fraction of radiated heat transmitted through the atmosphere to a target after reduction by atmospheric absorption and scattering

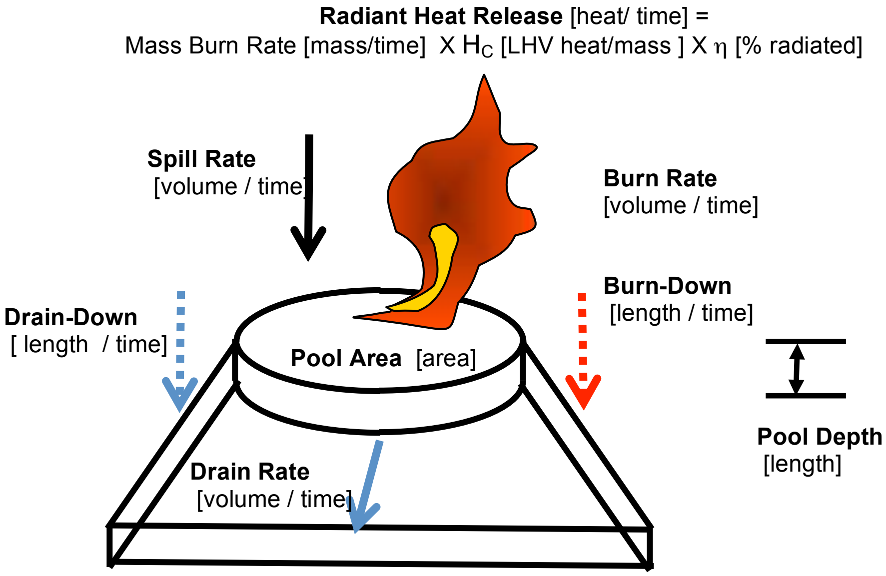

Figure 1. Radiation Exposure Limited by Fuel Supply Model

The fuel mass burn rate, m_B, calculation is discussed in the following sections. The parameter determinations of fraction of total heat radiated (η), the radiation view factor (F), and the radiation transmissivity (τ) are outside the scope of this paper.

2.1 Pool Fire Model

As determination of mass burned from the liquid spill is required to estimate the radiation, a pool fire model needs to be established. The assumption for the pool fire is that the heat released is limited by the amount of fuel in the pool. The pool of flammables is formed from a spill at grade. Some of the spilled material is drained away from the pool and some is burned.

When the pool fire has reached an equilibrium state, the amount of material drained away and burned off will equal the amount of material spilled. The pool is expanding over time until maximum pool diameter is reached. In general, the equilibrium state provides the largest pool fire as the liquid spill is no longer accumulating and forming the pool. Therefore, equilibrium state also provides the largest burn rate. By the material balance:

$$\dot{m}_S = \dot{m}_B + \dot{m}_D \qquad \text{… Eq. (2)}$$

where: $\dot{m}_S$ = liquid mass spill rate
$\dot{m}_B$ = liquid mass burn rate
$\dot{m}_D$ = liquid mass drain rate

Similarly, in volume based rates,

$$\dot{V}_S = \dot{V}_B + \dot{V}_D \qquad \text{… Eq. (3)}$$

where: $\dot{V}_S$ = liquid volume spill rate
$\dot{V}_B$ = liquid volume burned rate
$\dot{V}_D$ = liquid volume drain rate

2.1.1 Spill Rate

The spill rate is the liquid spilling to the ground resulting from an equipment leak. There are many commercial programs that calculate spill rates. To provide a spill rate, one has to postulate a leak scenario. Typically postulated is a hole or flange leak, which may be from adjacent equipment or the equipment exposed to the fire. If the spill originates at the equipment exposed to the fire, and depending on the release rate and duration, there may be different cases.

- A large leak will empty the equipment in a short period of time in an "instantaneous spill". With no internal fuel to vaporize and a large open leak hole, there will be no relief from the equipment.
- With a small leak but continuous flow of liquid fuel to the ground, the inventory will be depleted, but not until the equipment pressurizes and relieves. This is considered a “quasi-continuous spill”.
- A very small leak will produce a small relief load but for a longer period of time. The system will be slowly depleted. This leak could be classified as a “continuous spill”.

In this paper, a quasi-continuous spill is discussed further as this type of spill would result in a conservative relief load. The commercial program used in this paper [21] assumes that the rupture is an effective round hole with a specified area. The spill flow through the hole is calculated, and the liquid-to-grade is the flow through the hole minus fuel evaporated or entrained as mist. Although in reality, the flow through the hole could be in any direction, and consist of fine spray or a full stream, the model assumes the worst case that the spill is directed toward grade.

There are several considerations that are included in the model basis for the spill rate, such as leak location, leak stream inventory, leak equipment system pressure, atmospheric conditions, and leak stream properties.

2.1.2 Burn Rate

The total amount of liquid burned is correlated to the pool size [1]. The correlation uses the pool area and the rate of change in liquid level, also called the "burn-down" or vertical liquid consumption velocity. The rate of change in liquid level is not constant but a function of pool diameter. The larger the pool, the greater the rate of change in liquid level.

The general description is:

$$\dot{V}_B(volume/time) = \Delta\dot{L}_B\ (length/time)\ A_P(area) \quad \text{… Eq. (4)}$$

where: $\dot{V}_B$ = volume liquid burned
$\Delta\dot{L}_B$ = rate of change in liquid level burned or burn-down rate
A_P = pool fire area

As an assumption, only the pool is considered to burn and provide heat to the equipment. The liquid that is draining is assumed not to ignite, or if ignited, the burn is located far enough from the equipment that heat input is not significant. The equation below is for the case where the boiling point is above the initial spill liquid temperature.

$$\Delta\dot{L}_B\ (m/s) = 1.27 \times 10^{-6} \left(\frac{H_C}{\lambda_S + Cp\ \Delta T}\right) \left(1 - e^{-k\beta D}\right) \quad \text{… Eq. (5)}$$

where: λ_S = liquid spill latent heat of vaporization (heat/mass)
Cp = liquid spill heat capacity (heat/mass-temperature)
ΔT = temperature difference between normal boiling point and initial spill liquid temperature (temperature)
$k\beta$ = product of flame extinction-absorption coefficient and mean-beam-length corrector (length^{-1})
D = pool fire diameter (length)

The kβ coefficient is dependent on the material, and is based on experimental data [1].

2.1.3 Drain Rate

The total amount of liquid drained is correlated to the pool size. The correlation uses the pool area and the rate of change in liquid level, also called the "drain-down". The drain-down is a function of pool diameter.

The general description is:

$$\dot{V}_D(volume/time) = \Delta\dot{L}_D\ (length/time)\ A_P(area) \qquad \text{… Eq. (6)}$$

where: $\dot{V}_D$ = volume liquid drained
$\Delta\dot{L}_D$ = rate of change in liquid level drained or drain-down rate
A_P = pool fire area

The correlation used in this paper to determine the drain-down rate was developed in-house but is a variation based on the traditional empirical Manning equation for channel flow [22]. The correlation assumes that the draining liquid has been pooled with the pool effective diameter as the “width of flow” and pool depth as the “depth of flow”. The flammable liquids will drain down a channel with constant width and depth and a specified slope. NFPA requires a 1% slope or greater to prevent accumulation under piping and around tanks with a 1% slope generally providing adequate drainage [7]. There are a few publicly available drainage models suitable for this type of calculations and this is one area that is ready for more research.

In this paper, a typical pool depth of 10 mm is used. SFPE states that for an unconfined spill fire, the spill liquid will continue to spread until the pool is about 10 mm in depth [19]. Factors to be considered in estimating pool depth include, but not limited to, the following:

- Direction of spill affects the spill projection and the amount of liquid spill collected under or surrounding the subject equipment.
- Ground roughness impacts the collection of liquid spill, and thus the formation of pool fire. The higher the roughness level of the ground is, the higher the amount of liquid spill is collected.

2.2 Pool Fire Case Study

A case study is presented for a steady-state pool fire model which assumes that the fuel supply limits the heat flux to the equipment. The size of the pool is determined by the spill rate to grade, the amount of flammable liquids drained away from the pool and the amount burned. Conversely the amount burned and drained is a function of the pool size. Solving for the amount burned yields the heat radiated. The relief rate for the fire case is thus determined from the heat absorbed by the equipment from the heat radiated from the pool fire.

In this case study, the following assumptions / basis are made:

- Liquid spill originates from a 2” full bore break, located very close to the subject equipment and about 6 ft from grade. For example, this could be instrumentation piping failure. There is normally no flow through the piping.
- Liquid inside vessel is assumed to have 7 ft of liquid head above the piping break point. Liquid level in vessel decreases over time which reduces liquid head and thus, decreases the spill rate. For conservative calculation purpose, the liquid spill inventory is assumed to be very large such that the spill rate can be held constant at its maximum.
- Vessel normally operates at 100 psig and 306.1°F.
- The fluid composition is 4 mol% n-Butane, 6 mol% n-Hexane, and 90 mol% Dodecane, with the following properties:
  λs at atmospheric pressure = 25.3 Btu/lb
  H_C = 19,138 Btu/lb
  Cp = 0.625 Btu/lb°F
  NBP = 302.5°F
  ρ = 40.2 lb/ft^3
  Note that NBP is equal to the flashed liquid spill temperature.
- Product of flame extinction-absorption coefficient and mean-beam-length corrector, $k\beta$ = 0.34 ft^{-1}, based on the value of heavy alkanes.
- Fraction of total heat radiated, η = 0.30
  Radiation view factor, F = 0.392
- The environmental conditions are as the following:
  Ambient temperature = 80°F
  Wind speed = 2.24 mph
  Spill surface = concrete
  Ground slope = 2% to provide high drainage but uncomplicated construction
  Pool depth = 0.4 in.

2.2.1 Spill Rate

A commercial program [21] is used to determine the spill rate. The spill rate is the liquid condensate to the ground as shown below.

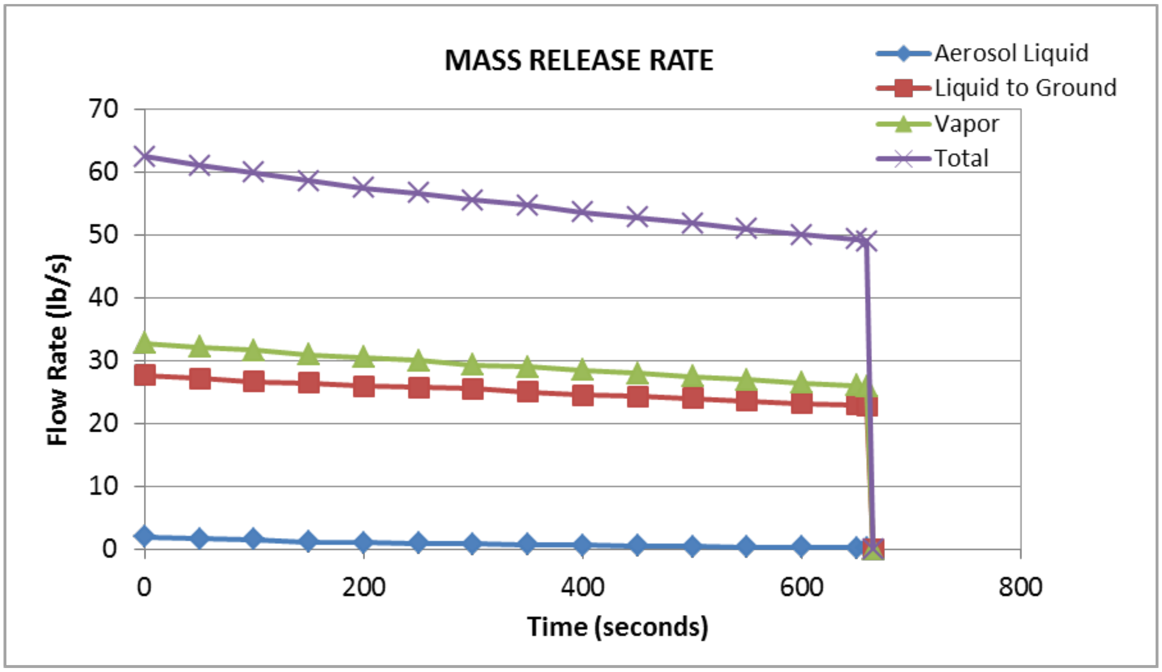

Figure 2. Spill Rate for Case Study

Liquid spill or liquid to ground is 28 lb/s or 0.697 ft^3/s. Vaporized liquid, including aerosol liquid, is 35 lb/s, which represents approximately 56 wt% flashed vapor. Assuming infinite spill liquid inventory, this maximum spill rate is to be held constant over a period of time until the equilibrium state or maximum pool diameter is reached.

2.2.2 Burn Down Rate

The burn down rate can be estimated using Eq. (5) above. The burn rate as a function of the pool diameter is then determined to be:

$$\Delta \dot{L}_B\ (m/s) = 1.27\times10^{-6}\left(\frac{H_C}{\lambda_S + Cp\ \Delta T}\right)\left(1 - e^{-k\beta D}\right)$$

$$\begin{aligned}\Delta \dot{L}_B &= 9.61\times10^{-4}\left(1 - e^{-0.34D}\right)\ \text{m/s}\\ &= 3.15\times10^{-3}\left(1 - e^{-0.34D}\right)\ \text{ft/s}\end{aligned}$$

2.2.3 Drain Down Rate

The total amount of liquid drained can be correlated to the pool size to facilitate the calculation of the steady-state pool size. At a 0.4-inch depth of flow, the drain-down rate can be represented in the following graph [22].

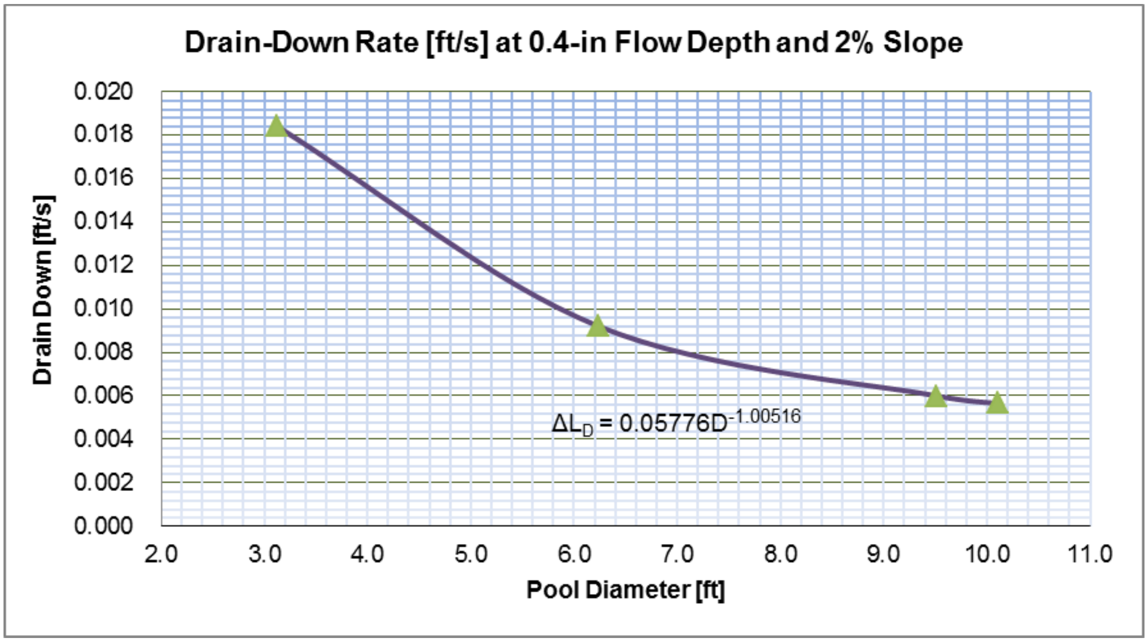

Figure 3. Drain Down Rate for Case Study

2.2.4 Material Balance and Pool Fire Diameter

Based on material balance where spill rate is equal to the sum of burn rate and drain rate,

$$\dot{V}_S = \dot{V}_B + \dot{V}_D \quad \text{or} \quad \dot{V}_S = \Delta\dot{L}_B\, A + \Delta\dot{L}_D\, A$$

where

$\dot{V}_S$ = spill rate
= 0.697 ft^3/s, as previously calculated in section 2.2.1

$\dot{V}_B$ = burn-down rate = $\Delta\dot{L}_B\, A$
= $3.15\times10^{-3}\,(1 - e^{-0.34D})\,A$, as derived in section 2.2.2
= $2.47\times10^{-3}D^2\,(1 - e^{-0.34D})$ ft^3/s

$\dot{V}_D$ = drain-down rate = $\Delta\dot{L}_D\, A$
= $(0.05776D^{-1.01})$ A, as shown in Figure 3 section 2.2.3
= $0.04536D^{0.99}$ ft^3/s

Solving simultaneously, the pool diameter, D, is calculated to be 10 ft. Consequently, the pool area, A, is calculated to be 80 ft^2. The burn rate, $\dot{V}_B$, and drain rate, $\dot{V}_D$, are calculated to be 0.244 ft^3/s and 0.453 ft^3/s, respectively. Therefore, the mass rate of fuel combusted, $\dot{m}_B$, is determined to be 35,300 lb/hr. Based on Eq. (1), the total heat absorbed used to calculate relief rate, Q_I, is determined to be 79.5 MMBtu/hr. This value is further used to calculate relief rate by dividing the value with the latent heat of process fluid in the subject equipment.

3. Conclusion

A model is presented to determine the heat release from a pool fire, based on the amount spilled, the fuel burned and amount drained. This model may be useful in a situation for a small pool fire or where the equipment exposed area is very large. API Std. 521 method assumes the fire heat input is limited by the equipment exposed surface area. On the other hand, the above method is limited by the fuel supply. One may use either method whichever constraint, surface area or fuel supply, is more limiting.

4. References

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[22] Bechtel Oil, Gas and Chemicals, Inc. A very special recognition to Jack O'Sullivan, Geotechnical and Hydraulics Engineering Services, who developed the drainage correlation.

5. Appendix – Examples of Methods

Following are a few simple examples of each method to explain the basis differences. There are many permutations of these in the literature.

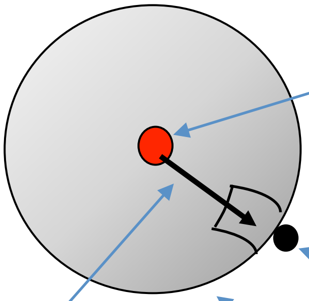
Appendix 5.1 Heat Input is limited by Fuel Supply

The method is characterized by the calculation of the amount of fuel combusted or heat release. The heat release is then translated to either a heat flux incident to equipment or a heat input to the equipment. This model assumes that the fuel supply limits the heat to the equipment. The greater the amount of fuel combusted, the higher the incident heat flux or heat release.

Appendix 5.1.1 Point Source

This model is familiar to those using the traditional pipe flare radiation calculations. The total heat generated by the amount of fuel combusted is radiated in all directions and is directed incident on the surface of effective sphere. If the target is at the same distance as the sphere from the source, the radiant heat flux at the target is the total heat release divided by the sphere surface area, with the heat at the sphere reduced by the amount absorbed by the atmosphere [τ] and the view factor [F]. The radiant heat flux at the target is then used to calculate the heat input onto the target surface area. The point source model is typically used for combustion sources far from the target.

Radiant Heat Flux Incident on the Target	$q_I = q_R \ \tau F$	..Eq. (A-1)
Radiant Heat Flux Incident on the Target	$q_I = Q_R \ \tau F / 4 \pi L^2$	..Eq. (A-2)
Total heat incident to the target and on an area of the target	$Q_I = q_I \ A$	..Eq. (A-3)
	$Q_I = Q_R \ \tau \ F \ A \ / 4 \pi L^2$	..Eq. (A-4)



$Q_R = m_B \ H_C \ \eta$

where

Q_R is radiant heat release from the combusted fuel [Btu/hr]

m_B is mass rate of fuel combusted [lb/hr]

H_C is the lower heating value [Btu/lb]

η is the fraction of total heat radiated

- q_R is the radiant heat flux of flame
- q_I is the radiant heat flux incident to the target [Btu/hr-ft^2]. This is also called the radiation intensity
- Q_I is the radiant heat to the target [Btu/hr]
- A is an exposed area of the target that is absorbing heat [ft^2]

τ is atmospheric transmissivity

F is view factor

Surface area of the effective sphere is 4 π L^2 where L is the distance from the source to the sphere.

Appendix 5.1.2 Pool Fire Close to Target

This is the simple model used in this paper. The primary assumption is that the pool fire is adjacent to the equipment and the amount of radiation absorbed by atmosphere is negligible ($\tau = 1.0$). The heat of combustion from the amount of fuel burned is radiated to the target. The model as formulated does not directly require an exposed surface area, although a view factor F if included would limit the heat transfer. This model is useful if the fire is small or if the equipment has a very large exposed area.

$$Q_I = Q_R \; F \qquad \ldots \text{ Eq. (A-5)}$$

where

Q_I is the radiant heat to the target [Btu/hr]

Q_R is the radiant heat release from the combusted fuel [Btu/lb] = $m_B \; H_C \; \eta$

m_B is the mass rate of fuel combusted [lb/hr].

H_C is the lower heating value [Btu/lb]

η is the fraction of total heat radiated

F is a view factor

Appendix 5.2 Heat Input is limited by Heat Flux and Equipment Exposed Area

The method is characterized by the calculation of the heat flux incident to equipment, with the implicit assumption that there is sufficient fuel to generate that heat flux. Thus this steady-state model assumes that the heat flux and exposed area limit the heat to the equipment.

Appendix 5.2.1 API-NFPA Model for Vessel Fires

This model is the workhorse of the hydrocarbon process industries and is detailed in many popular standards [2–10] and also adopted by several specialty standards. The equations for the heat flux differ often between standards, depending on the use and organization. Additionally, the correlating “environmental” factors also differ. The factors are used to adjust the model based on alternate assumptions such as view factors, insulation, fuel type, drainage, apparent heat transfer coefficients for liquid and vapor and other parameters. Because of the simplifying parameters, this model is designed for large tanks located at a grade susceptible to a pool fire and essentially full of liquid. In this situation, heat input to the vapor space and heat input at high elevations are ignored compared to the heat input to the wetted area and lower elevations. Several standards and articles provide commentary and references on the development of the equations [2, 3, 7, 14]. Additionally, there is a large literature on discussion of the parameters and variations on this method; the following are some typically referenced [12-18].

The heat flux from the fire is reduced by correlating factors. The example presented actually calculates the heat absorbed from the incident heat flux and exposed area. This example is taken from either reference [2, 6]. The starting point is calculation of the heat flux absorbed from the radiant heat flux or flame emissive power.

$$q_A = q_R \;\; F \;\; \tau \;\; E_1 \;\; E_2 \qquad \text{… Eq. (A-6)}$$

Since this model limits the heat input to the amount absorbed through the area, the heat absorbed is defined from the area and radiant heat flux

$$Q_A = q_A \; A \;\; = q_R \;\; A \;\; F \;\; \tau \;\; E_1 \;\; E_2 \qquad \text{… Eq. (A-7)}$$

With parameters substituted

$$Q_A = 21{,}000 \; A^{0.82} \;\; E_2 \qquad \text{… Eq. (A-8)}$$

where

Q_A is the heat absorbed by the fluid through an area of the target [btu/hr]. Since the heat absorbed is based on actual fire experiments, it represents both convection and radiation and re-radiation from the target. This heat differs from other models which calculate incident radiation

A is an exposed area of the target that is absorbing heat [ft^2]. Typically the area is the wetted area with the assumption that the heat absorbed to an un-wetted are is about one-third of that absorbed through the wetted area and is neglected.

q_A is the heat flux absorbed at the target [btu/hr-ft^2] including convection and radiation as reduced by factors.

q_R is the fire heat flux [btu/hr-ft^2], also called the flame emissive power. The value used in the standard is 34,500. When adjusted by the environmental factor E_1, the value is 21,000. Unlike the solid flame model, this is a constant and thus related to any flame shape.

τ is equal to 1 since there is little heat absorbed by the atmosphere.

F is a view factor defined by ($1 / A^{0.18}$). This indicates that as the wetted is larger, there is less heat flux.

E_1 is an "environmental" factor used to represent good drainage and firefighting with a value of 0.609

E_2 is an "environmental" factor that represents the effect of insulation on heat transfer. Although this factor should be additive, the use of a multiplier is sufficient for the accuracy of the model. The factor is also used to represent heat absorbed by deluge water.

Appendix 5.2.2 Solid Flame Model

The solid flame model is used extensively since the radiant heat flux or flame emissive power can be calculated several ways. They are simple to use for engineering, may model pool fires and severe fires, and maybe steady or unsteady. These models are sometimes described as analytical, to distinguish from the more empirical NFPA-API models. The earlier analytical models, such as many cited in API Standard 521 [2], apply more simplifying assumptions than more recent models which exploit increased computational efficiency. Although powerful and flexible tools, these pool fire models have some limitations in process engineering relief system design [11]. The starting point is calculation of the incident heat flux. There are several typical methods for calculating the radiant heat flux or emissive power.

$$q_I = q_R \ F \ \tau \qquad \ldots \text{Eq. (A-9)}$$

- Surface Emissive Power E_F

The radiant heat flux q_R may be formulated as an emissive power E_F. Depending on the model, it may be a time-averaged emissive power or calculated from the radiant heat release from the combusted fuel, calculated using empirical formulas.

$$q_R = E_F \qquad \ldots \text{Eq. (A-10)}$$

- Stefan Bolzmann

The radiant heat flux q_R may also utilize the Stefan-Boltzmann equation to relate temperature of the fire to the heat flux absorbed by the equipment.

$$q_R = q_B \ \varepsilon \qquad \ldots \text{Eq. (A-11)}$$

$$q_B = \sigma (T^4_F - T^4_A) \qquad \ldots \text{Eq. (A-12)}$$

and

$$q_R = \sigma (T^4_F - T^4_A) \ \varepsilon \qquad \ldots \text{Eq. (A-13)}$$

where

q_R is the flame radiant heat flux or emissive power.
q_B is the black body emissive power.
σ is the Stefan Bolzmann constant
T^4_F is the flame temperature
T^4_A is the ambient temperature
ε is emissivity

Appendix 5.3 Computational Fluid Dynamics (CFD)

At the sophisticated end of the spectrum are models based on three-dimensional computational fluid dynamics (CFD) which solve unsteady-state flow, heat and mass transfer, often with reaction mechanisms for soot formation. Much of the current research in fire modeling is in this field. Presently the methods are very complicated for typical process engineering work.