THERMAL RADIATION HAZARDS FROM THE IGNITION OF EMERGENCY VENTS

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SYNOPSIS

When flammable gases or vapours are discharged to atmosphere from emergency relief vents, ignition may occur. The resulting flame on the vent pipe, which may be turbulent, will shed thermal radiation on adjacent plant and personnel. By considering the possible size, shape and temperature of this flame, the thermal radiation falling on surfaces in the vicinity of the vent can be calculated. These calculated values may then be compared with the known effects on various materials and human beings to enable vents to be designed and positioned with safety.

Introduction

Nearly all process vessels in chemical plants which may contain gases or vapours under pressure are fitted with some sort of relief device. If the pressure within any particular system rises due to excessive heating or chemical reaction the relief device opens to allow gas or vapour to be vented to atmosphere thus preventing the pressure within the vessel from exceeding maximum designed limits. The vent usually relieves the pressure into a pipe through which the discharge is led away to atmosphere in a safe place.

It has been observed, however, that on certain occasions when such a discharge has been of flammable material, ignition has occurred and a fierce flame has formed in the vent pipe. Such a flame may be highly turbulent giving efficient combustion and thereby producing a high intensity of thermal radiation.

This paper concerns the thermal radiation hazard which may exist in the vicinity of such a burning fuel jet. A general method is given to predict the probable size and shape of the flame, the temperature and radiation from the flame, and the resulting radiation flux on the surroundings. By way of illustration the radiation produced by the discharge of butane gas from a three-inch diameter vent pipe is taken as an example at each stage.

Finally, data on the known effects of thermal radiation are considered and compared with the levels of radiation which might be expected from vent flames, thereby enabling criteria of safe operation to be established.

Theory

Stability of vent flames

It will be assumed throughout this paper that the fuel jet produced by the emergency discharge of vapour, initially under pressure, will be turbulent. In the event of ignition the turbulent flame may be stable on the vent. Above a certain velocity turbulent flames become detached from the orifice, a phenomenon known as "lift-off" occurs, and with higher velocities the gap between the bottom of the flame and the orifice becomes greater and eventually the flame may blow-out. The phenomenon has been investigated by Wohl, Kapp, and Gazley[1] and the results of their work may be summarized as follows. Most of the work was done with

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mixtures of fuel and air and the effects of pure fuel jets can only be inferred by extrapolation. It is clear, however, that the higher the concentration of fuel in the original jet the greater will be the critical discharge velocity before blow-out. It is also evident from this work that the larger the orifice size the greater will be the critical discharge velocity before blow-out. Some of the results of this work are summarized in Table I. Although the values in brackets in Table I are obtained by extrapolation, it seems likely that pure fuel jets on the size of vents usually encountered on chemical plant will form stable turbulent flames which will not blow out even at sonic discharge velocities.

TABLE I.—*The Effect of Concentration of Fuel and Size of Orifice on Observed Blow-out Velocity*

Butane in Air (%)	Internal Diameter of Orifice (in)	Blow-out Velocity (ft/s)
100	0·045	120
100	0·087	150
60	0·18	180
(100)	(0·18)	(300)
25	0·40	100
(100)	(0·40)	(400)

Size and shape of flame

It has been shown by Hottel and Hawthorne[2] that the length of a turbulent diffusion flame is independent of the discharge velocity. Hawthorne, Weddell, and Hottel[3] give a simple formula for calculating the dimensions of such a flame, with experimental results in support. According to Hawthorne, Weddell, and Hottel, the ratio of the flame length, L, to the orifice diameter, D, is given by:

$$\frac{L}{D} = \frac{5 \cdot 3}{C_T} \sqrt{\left\{ \frac{T_F}{T_N} \frac{1}{a_T} \left[C_T + (1 - C_T) \frac{M_S}{M_N} \right] \right\}} \qquad (1)$$

where:

C_T = the molar concentration of fuel in the stoichiometric mixture.

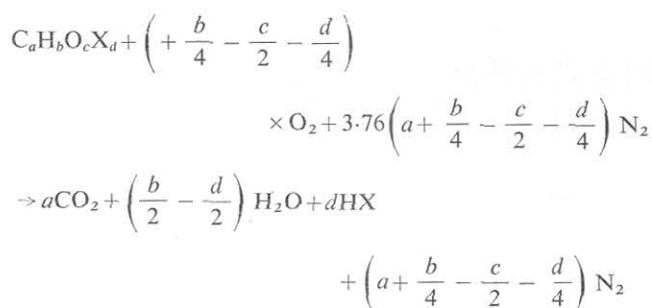T_F = the flame temperature (°C).

T_N = the temperature of the vapour leaving the vent orifice.

a_T = the molar ratio of reactants to products.

M_S/M_N = the ratio of the molecular weights of the surrounding atmosphere to that of the gas issuing from the nozzle.

The stoichiometric combustion of one mole of fuel of general formula $C_a H_b O_c X_d$ (where X is a halogen) in air may be represented by:

$$C_a H_b O_c X_d + \left(+ \frac{b}{4} - \frac{c}{2} - \frac{d}{4} \right)$$

$$\times O_2 + 3 \cdot 76 \left(a + \frac{b}{4} - \frac{c}{2} - \frac{d}{4} \right) N_2$$

$$\rightarrow a CO_2 + \left(\frac{b}{2} - \frac{d}{2} \right) H_2O + d HX$$

$$+ \left(a + \frac{b}{4} - \frac{c}{2} - \frac{d}{4} \right) N_2$$

The total number of reactant moles is given by:

$$N_R = 4 \cdot 76 \left(a + \frac{b}{4} - \frac{c}{2} - \frac{d}{4} \right) + 1 \qquad (2)$$

and the number of product moles:

$$N_F = a + \frac{b}{2} + \frac{d}{2} + 3 \cdot 76 \left(a + \frac{b}{4} - \frac{c}{2} - \frac{d}{4} \right) \qquad (3)$$

and equation (1) becomes:

$$\frac{L}{D} = 5 \cdot 3 N_R \bigg/ \sqrt{ \left\{ \frac{T_F}{T_N} \frac{N_F}{N_R} \left[\frac{1}{N_R} + \left(1 - \frac{1}{N_R} \right) \frac{M_S}{M_N} \right] \right\} } \qquad (1a)$$

If it is assumed that the final flame temperature at stoichiometry is 2300 K (see next section) substitution in equation (3) using butane at 30°C as an example gives:

$$\frac{L}{D} = 5 \cdot 3$$

$$\times 31 \cdot 0 \bigg/ \sqrt{ \left\{ \frac{2300}{300} \frac{33 \cdot 4}{31 \cdot 0} \left[\frac{1}{31 \cdot 0} + \left(1 - \frac{1}{31 \cdot 0} \right) \frac{28 \cdot 5}{58} \right] \right\} }$$

$$= 360$$

Hence the turbulent discharge of butane from a three-inch pipe would give a turbulent flame approximately 90 ft high.

The shape of the turbulent flame envisaged in Hawthorne's treatment[3] is an inverted cone with its apex at the vent orifice such that:

$$\frac{L}{D} = 5 \cdot 3 \frac{W}{D} \qquad . \qquad . \qquad . \qquad (4)$$

where W is the diameter at the top of the flame.

Hence $L = 5 \cdot 3 W$ giving a butane flame of 17 ft diameter at the top as depicted in Fig. 1.

Temperature of the turbulent flame

Methods are available for computing the maximum flame temperatures of flammable gas or vapour mixtures with air but these are rather tedious (see Ref. 4). It is recommended, therefore, that for the purposes of the hazards analysis this step should be replaced by the simple assumption that the flame temperature will not exceed 2300 K.

The observed maximum flame temperatures of a number of fuels in air are given in Table II reproduced from Refs 5 and 6.

It can be seen from Table 2 that with the exception of acetylene the combustion of hydrocarbons in air does not give temperatures in excess of 2300 K. Although not reported in Table II, fuel containing oxygen or halogens will have

flame temperatures much less than those of the parent hydrocarbon with certain exceptions, for example, peroxides and nitrocompounds. By assuming a flame temperature of 2300 K for example, acids, alcohols, aldehydes, ethers, and esters, a large margin of safety will be introduced since the resulting radiation is a function of the fourth power of the absolute temperature of the flame.

TABLE II.—*Maximum Flame Temperatures of Various Fuels Burning in Air*

Fuel	$T°$ max. (K)
Acetylene	2600
Butane	2170
iso-Butane	2170
Butylene	2200
Carbon monoxide	2220
Ethane	2170
Ethylene	2250
Hydrogen	2315
Methane	2150
Propane	2200
Propylene	2200

Radiation

RADIATION FROM THE FLAME

The radiation flux produced by a flame is given by:

$$I = e S T^4 \qquad . \qquad . \qquad . \qquad (5)$$

where:

e = the emissivity.

S = Stefan's constant ($= 1 \cdot 37 \times 10^{12}$ cal/cm³ s K⁴).

T = absolute flame temperature (K).

The emissivity is a complex function of the molecular species in the flame and the effective path length, that is, flame thickness. For path lengths of five feet or over, however, the emissivity approaches unity and:

$$I_0 = S T^4 \qquad (6)$$

This relationship is therefore used with this limitation in mind and in consequence has a constant value throughout this report of:

$$I_0 = 1 \cdot 37 \times 10^{-12} \times 2300^4 \qquad \text{cal/cm}^2 \text{ s}$$
$$= 38 \cdot 3 \text{ cal/cm}^2 \text{ s } 508\,000 \qquad \text{Btu/ft}^2 \text{ h}$$
$$= 160 \text{ W/cm}^2$$

Henceforth watts per square centimetre will be used as the units for energy flux.

RADIATION FLUX IN THE VICINITY OF THE FLAME

The radiation flux in the vicinity of the flame is given by:

$$I_x = \phi I_0 \qquad . \qquad . \qquad . \qquad (7)$$

where ϕ is the configuration factor or view factor of the flame from any point, x. Since I_0 is affected by the emissivity, I_x cannot always be determined simply by consideration of the flame shape. At a point, Y, for example in Fig. 1 the radiation will be coming from all points along the length of the flame. The radiation intensity from F will be greater than that from G because G is in a section of flame where the emissivity is very low. Not only is the cone very narrow at G but the actual combustion process at G will only be taking place close to the surface. The cross-sectional area of the jet at G will contain largely pure fuel and there is even the possibility of lift-off in this region (see above). In order to estimate the radiation flux at a point Y some assumptions have to be made about the effective shape of the flame to be considered as a radiator. This is true for a large number of points in the space around the flame.
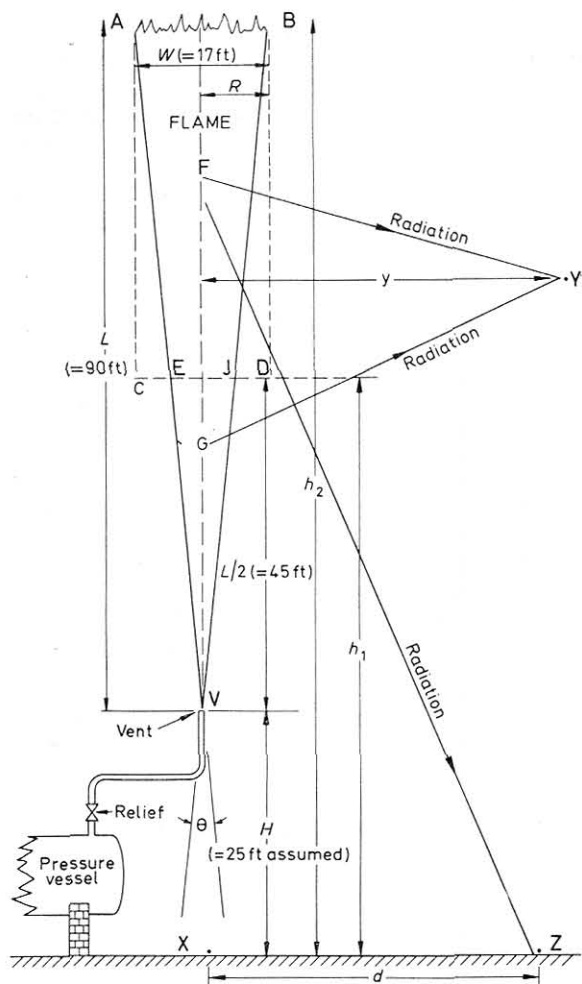
Fig. I—*Proposed structure of a turbulent diffusion flame resulting from the discharge of butane from three-inch diameter vent*

At the point X in Fig. 1, however, directly beneath the vent the flame appears to be a disc with an emissivity of unity. The configuration factor of the flame at X, within the solid angle θ, will be the same as a disc of radius R (from equation (4)) at a distance $L+H$ where L is the flame length and H is the stack height above X (see " equivalent radiator ").[7] The configuration factor of such a disc is:

$$\phi_x = \frac{R^2}{(L+H)^2 + R^2} \qquad (8)$$

(See Ref. 7)

Returning to our example as depicted in Fig. 1 and assuming that the vent stack rises to a height of 25 ft above the ground:

$$\phi_x = \frac{8\cdot5^2}{(91+25)^2 + 8\cdot5^2}$$

$$\phi_x = 0\cdot0058$$

Hence:
$$I_x = \phi_x I_0$$

$$0\cdot93 \text{ W/cm}^2$$

It can be seen from equation (8) that where $H = 0$, that is, in the immediate vicinity of the vent V the radiation flux is:

$$I_V = \phi_V I_0$$

$$= \frac{R^2}{L^2 + R^2} I_0$$

$$= 1\cdot33 \text{ W/cm}^2$$

Since the ratio L/R is a constant (see above), the radiation flux immediately beneath the vent will be independent of the type of fuel or the size of vent orifice.

Points between X and V in Fig. 1 will be subject to radiation fluxes of between 0·93 and 1·33 W/cm².

It has already been pointed out that because of low emissivity at the lower half of the flame the radiation at Y is difficult to compute accurately. Some indication of the level of radiation at Z is, however, necessary to estimate the hazard on the ground at a point to one side of the flame axis since this may be higher than at X.

In order to estimate the radiation flux at Z it is assumed that the flame is equivalent to a rectangular radiator ABCD as shown in Fig. 1. Once again the approximation will give a bigger value than will occur in practice since it assumes that the edges of the cone will radiate with unit emissivity to the point Z.

The configuration factor of the rectangle ABCD is given by:

$$\phi_Z = \frac{dR}{\pi} \frac{1}{h_1^2 + d^2} - \frac{1}{h_2^2 + d^2} \qquad (9)$$

(see Appendix).

In equation (9):
$$h_1 = H + L/2$$
$$h_2 = H + L$$

(See Fig. 1.)

Values of ϕ_Z at various distances along the ground from the axis of the flame (X in Fig. 1) are given in Table III. It can be seen that, in the example chosen, the radiation intensity increases to a maximum and then falls away rapidly with increasing distance from the flame axis.

TABLE III.—*Configuration Factor and Vertical Radiation Intensity at Various Distances from the Axis of the Flame at Ground Level*

Distance From Flame Axis (ft)	Configuration Factor	Radiation Flux (W/cm²)
20	0·0062	0·99
30	0·0082	1·31
40	0·0093	1·48
50	0·0098	1·56
60	0·0094	1·51
80	0·0081	1·30
100	0·0065	1·04

Some indication of the horizontal flux (at Y in Fig. 1) is required to estimate the radiation hazard to any nearby tall structures. It can be seen however that in this direction a proportion of the horizontal radiation is originating from the thin part of the flame. The radiation flux at a point about ten times the maximum cone diameter would be very approximately:

$$\phi_Y \simeq \frac{RL}{\pi y^2} \qquad . \qquad . \qquad . \qquad (10)$$

This is the effect of an equivalent radiator of area $\frac{3}{4}RL$ (that is, ABEJ in Fig. 1) at a distance y with radiator and receiver parallel to each other. In the chosen example this would give a view factor of 0·0063 at a distance of 170 ft (that is, ten flame diameters) resulting in radiation intensity of about one watt/square centimetre.

Jet reaction

At this point we should consider briefly the consequences of the discharge of gas, and hence the axis, not being vertical. The area directly under the flame will obviously be under the influence of a larger configuration factor and it is therefore

essential that the vent pipe cannot be deflected by the jet reaction at the orifice. If the jet reaction were sufficient to bend the vent pipe through more than 90° the consequences would be very serious.

The jet reaction, J, can be calculated from the momentum change in the vapours issuing from the vent and is given by:

$$J = \frac{\rho V U}{32} \quad \text{(pounds force)} \quad (11)$$

where:

ρ = the vapour density (lb/ft³).

V = the volume discharge rate (ft³/s).

U = the discharge velocity (ft/s).

In the case of the sonic discharge of butane through a three-inch diameter orifice the jet reaction would be:

$$J = \frac{0 \cdot 170 \times 49 \times 730}{32} = 190 \, \text{lbf}$$

The vent supports should be designed to withstand this reaction with a margin of safety.

Effects of Thermal Radiation

The maximum temperature to which any surface can be raised by the absorption of thermal radiation is dependent upon the intensity of the radiation. The maximum (equilibrium) temperatures resulting from various levels of radiation are given in Table IV (see Ref. 8).

TABLE IV.—*Maximum (equilibrium) Temperatures Resulting from Various Intensities of Radiation*

Radiation Intensity (W/cm²)	Equilibrium Temperature (°C)
0·2	160
0·5	230
1·0	320
1·4	390

The temperatures in Table IV represent maxima which can only be attained in the absence of conduction and convection from the irradiated surface. In practice the radiation equilibrium temperature is seldom reached and in order to assess the possible effects of any level of thermal radiation we must consider observed effects.

Some observed effects of various levels of radiation intensity are listed in Table V.

It can be seen from Table V that between 0·64 W/cm² and 1·25 W/cm² thermal radiation begins to have undesirable effects on people and objects. At a radiation flux of 0·64 W/cm² any human being has about eight seconds in which to run away to an area where the thermal radiation is small and during this time blistering of the skin would not be expected to occur. (Blistering of skin occurs after five seconds at exposure to radiation of 1·6 W/cm²).

TABLE V.—*Effects of Thermal Radiation*

Radiation Intensity (W/cm²)	Observed Effect
0·067	Summer sunshine in U.K. (Ref. 9)
0·64	Pain after 8 s exposure (Ref. 10)
1·04	Pain after 3 s of exposure (Ref. 9)
1·25	Just sufficient for wood to ignite after prolonged exposure and a ½ inch pilot flame in contact with the surface (pilot ignition) (Ref. 9)
1·6	Blistering of skin after 5 s (Ref. 10)
2·9	Wood ignites spontaneously after prolonged exposure (Ref. 9)
4·2	Cotton ignites in 5 s (Ref. 9)
5·2	Fibre-board ignites in 5 s (Ref. 9)

Discussion

It has been assumed that the flame resulting from ignition of an emergency discharge vent will be highly turbulent and that combustion will be similar to that of a premixed flame. It is possible however, that in the final stages of the discharge the gas velocity may fall and a conventional diffusion flame may be produced momentarily before the flow of fuel ceases. Such a flame may be slightly larger than the turbulent flame but the flame temperature will be much less and therefore the radiation hazard will be less than that produced by the turbulent flame.

It can be seen from equation ($1a$) that larger flames will be produced by fuels requiring more air for combustion, that is, with higher values of N_R. The effect of this is greater than the small reduction resulting from the increase in molecular weight, M_N. There is in consequence a greater thermal radiation hazard from the discharge of a heavy hydrocarbon (for example, styrene) than from a lighter one (for example, ethylene) or one requiring less air for combustion (for example, vinyl chloride). In this respect butane is a typical example in the middle range of the types of gases and vapours which may be encountered in this sort of situation.

With any fuel, however, there will be a thermal radiation hazard in the vicinity of an emergency discharge vent flame. The hazard will be greater alongside than it will be directly beneath the flame. It can also be seen that the view factor of the flame from any position is directly proportional to the square of the vent diameter. There is therefore a distinct advantage in keeping this as small as possible. The size of the vent should therefore be limited to the minimum which is necessary to prevent pressurisation of the plant above its maximum design strength. This vent should then be supported in such a way that it does not move under the influence of the jet reaction and in such a position that the thermal radiation does not affect nearby plant or personnel.

It is recommended, therefore, that vent stacks should be designed in such a way that areas frequented by personnel could not be exposed to radiation in excess of half a watt per square centimetre in the event of discharge and ignition. This may involve raising the height of vent stacks relative to working areas. Alternatively, access could be limited in those areas where a burning discharge could give radiation in excess of half a watt per square centimetre to periods when the associated plant is off-line. In areas where the radiation flux could approach the specified limiting value evacuation should be possible within ten seconds.

Although equipment can absorb greater amounts of thermal radiation than people it is not usually possible to move equipment away from the radiation source. Most equipment should be safe in a radiation flux of about one watt per square centimetre for many minutes since even wood will only catch fire, with pilot ignition, after prolonged exposure in a thermal radiation flux of 1¼ W/cm². It may be impossible to design the vent stack in such a way that all the metal hardware on and around the stack does not receive radiation in excess of one watt per square centimetre but adjacent plant and roofs should not be exposed to higher levels of radiation.

Adopting 0·5 W/cm² and 1·0 W/cm² for the maximum permissible levels of radiation for personnel and plant would be in general agreement with safety limits from other sources. Tan[10] recommends these two values for the maximum levels of radiation from flare stacks. The recommendation concerning the maximum exposure of buildings to radiation from fires in adjacent buildings is 1·25 W/cm² (Ref. 11) and in the tests which are carried out to determine the fire resistance of roofing materials similar levels of radiation are used.[12] Thus, for the fire penetration test, the specimen is exposed to a radiation intensity of 1·44 W/cm² for one

hour and to a maximum of 0.9 W/cm^2 in the presence of a pilot flame for flame-spread. A class A.A. material must show no penetration or flame-spread under these conditions and would, therefore, be suitable in plant which has been designed to limit thermal radiation to 1.0 W/cm^2.

Appendix

The configuration factor of the rectangle ABCD at X in Fig. 2 is given by:

$$\phi_1 = \frac{1}{\pi} \left\{ \tan^{-1} \left(\frac{x}{d} \right) - \frac{d}{\sqrt{(h_1{}^2 + d^2)}} \tan^{-1} \left[\frac{x}{\sqrt{(h_1{}^2 + d^2)}} \right] \right\}$$
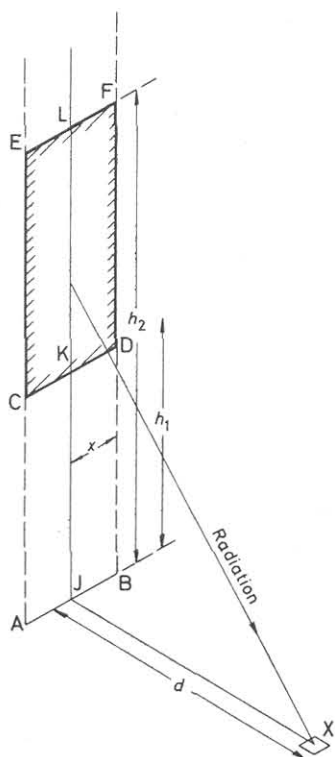

Fig. 2—Configuration factor of the rectangle CDEF to point X

This is obtained from Ref. 8 taking the configuration factor of ABCD as twice the value AJCK.

It follows that the configuration factor for a rectangle of base AB but infinite height is:

$$\phi_2 = \text{AB to infinity} = \frac{1}{\pi} \left[\tan^{-1} \left(\frac{x}{d} \right) \right]$$

since $h_1 = \infty$

and hence the configuration factor of a rectangle of base CD but infinite height is $\phi_3 = \phi_2 - \phi_1$:

$$\phi_3 = \frac{1}{\pi} \left\{ \frac{d}{\sqrt{(h_1{}^2 + d^2)}} \tan^{-1} \left[\frac{x}{\sqrt{(h_1{}^2 + d^2)}} \right] \right\}$$

If, however h_1 and d are large compared with x, that is, $\sqrt{(h_1{}^2 + d^2)} > 10x$, then:

$$\phi_3 \simeq \frac{dx}{(h_1{}^2 + d^2)}$$

Since the configuration factor of the rectangle EF to infinity is similarly:

$$\phi_4 \simeq \frac{dx}{(h_2{}^2 + d^2)}$$

The confinguration factor of the rectangle CDEF is:

$$\phi_5 = \phi_3 - \phi_4 = \frac{dx}{\pi} \left[\frac{1}{(h_1{}^2 + d^2)} - \frac{1}{(h_2{}^2 + d^2)} \right]$$

$$\phi_5 = \frac{dx}{\pi} \frac{(h_2{}^2 - h_1{}^2)}{(h_1{}^2 + d^2)(h_2{}^2 + d^2)} \qquad \text{(approximately)}$$

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