First Semester Examination
Academic Session 2020/2021

February 2021

EAF526 – Fire Behaviour

Duration : 2 hours

Please check that this examination paper consists of **TWELVE (12)** pages of printed material including appendix before you begin the examination.

Instructions : This paper contains **FOUR (4)** questions. Answer **ALL** questions.

Each question **MUST BE** answered on a new page.

(1). (a). Fire and explosion are the two main incidents that cause significant damages to equipment and deaths. To prevent accidents resulting from fire and explosion, engineers should be familiar with their natures, chemistry, and physics.

(i). Differentiate the occurrence of pool, jet, and flash fire.

[10 marks]

(ii). Evaluate the effect of pool fire with large diameter on the radiation heat flux. Justify your answer based on the radiation heat flux equation.

[15 marks]

(2). During a fire incident, approximately 28.3 m^3 of petrol was spilled and ignited, resulting in a flame from a 2 cm thickness of pool. Based on the following data:

Boiling temperature, T_b : 423 K
Heat of combustion, ΔH_c : 45 000 kJ/kg
Heat of vaporization, ΔH_v : 370 kJ/kg
Specific heat capacity, C_p : 2.21 kJ/kg.K
Ambient temperature, T_a : 298 K
Soot surface emitting power, SEP_{soot} : 20 kW/m^2
Wind velocity, u_w : 5 m/s
Density of air, ρ_{air} : 1.21 kg/m^3
Viscosity of air, η_{air} : 16.7 x 10^{-6} Pa.s
Saturation water vapor pressure, P_w° : 2320 Pa
Relative humidity : 0.7

(a). Determine the heat flux 20 m from the flame's surface in the direction of the wind.

[15 marks]

(b). Analyse the probability of injury (1^{st} and 2^{nd} degree burns) and death at 20 m away from the flame's surface.

[6 marks]

(c). Given the population density is about 1 person per 20 m^2 in that area, predict the number of persons with 1^{st} and 2^{nd} degree burns, as well as the number of deaths.

[4 marks]

(3). (a). With the aid of sketches, discuss any **THREE (3)** stages of enclosure fire development in terms of pressure and flow of the hot and cold gases.

[15 marks]

(b). An atrium will be equipped with the automatic mechanical smoke ventilation that will be started by means of a heat detector at the ceiling. The heat detector will be activated if the temperature rises are in the range of 40-70°C above the ambient temperature. Design the range of heights for the atrium such that the heat detector could detect the heat from a 2.5 m^2 diesel oil pool fire.

[10 marks]

(4). (a). Fire development in an enclosure greatly depends on both enclosure openings and ventilation flow. By segmenting curve **B** in **Figures Q4(a)** and **Q4(b)** into several important sections, analyse how curve **B** in each figure deviates from the hypothetical growth rate curve **A**.

[10 marks]

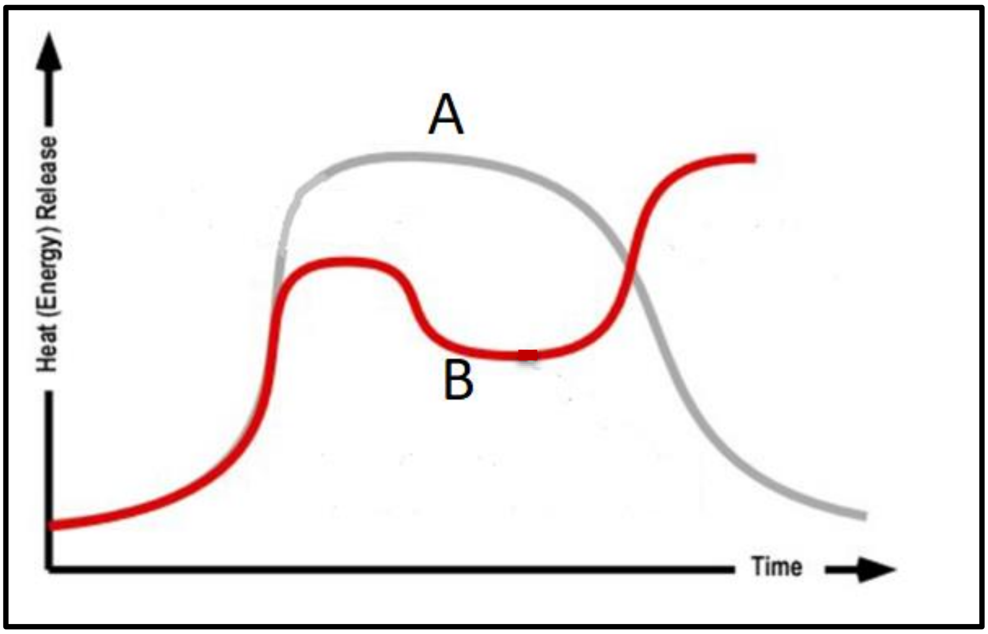

Figure Q4(a)

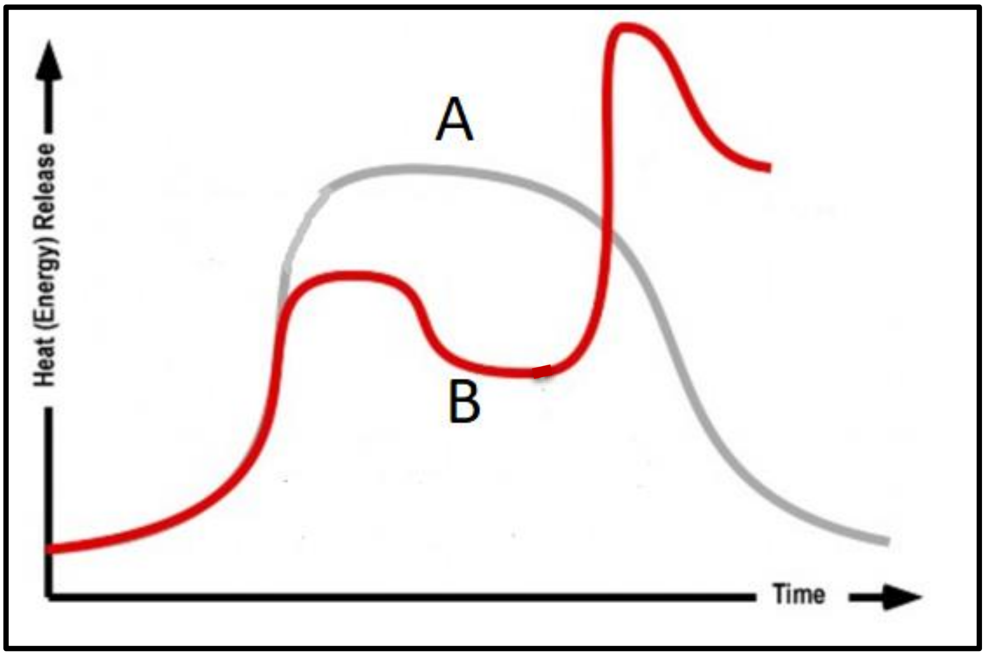

Figure Q4(b)

(b). A room fire produces an energy release rate that increases linearly from zero to 1 MW in 10 minutes and remains constant. The room with 150 mm thick wall has dimensions of 5.5 m by 3.5 m by 3.0 m high. There are two windows 1.0 m by 1.0 m each in the room.

(i). By selecting a preferred material of construction, outline the steps taken to predict the temperature inside the room at a particular time.

[3 marks]

(ii). Calculate the gas temperature at time 5 minutes from ignition.

[6 marks]

(iii). Evaluate the possibility of flashover to occur in 10 minutes.

[6 marks]

APPENDIX

C_p, heat capacity of air	1.00	kJ/(kgK)
g, Gravitational constant	9.81	m/s^2
C_d, orifice discharge coefficient	0.7	

Density (kg/m^3) = 353/T (T in K)

IDEAL PLUME	
$b = \frac{6}{5}\alpha z$ $u = 1.94\left[\frac{g}{c_p T_\infty \rho_\infty}\right]^{1/3} \dot{Q}^{1/3} z^{-1/3}$	$\dot{m}_p = 0.20\left[\frac{\rho_\infty^2 g}{c_p T_\infty}\right]^{1/3} \dot{Q}^{1/3} z^{5/3}$ $\Delta T = 5.0\left[\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right]^{1/3} \dot{Q}^{2/3} z^{-5/3}$

ZUKOSKI PLUME
$\dot{m}_p = 0.21\left[\frac{\rho_\infty^2 g}{c_p T_\infty}\right]^{1/3} \dot{Q}^{1/3} z^{5/3}$ $\qquad$ $\dot{m}_p = 0.071\dot{Q}^{1/3} z^{5/3}$

HESKESTAD PLUME

$$z_o = 0.083\dot{Q}^{2/5} - 1.02D$$

$$\text{L}= 0.235\dot{Q}^{2/5} - 1.02D$$

$$\dot{Q}_c = 0.6\,\dot{Q}\ to\ \dot{Q}_c = 0.8\,\dot{Q}$$

$$\dot{Q}_c = \dot{m}_p c_p \Delta T$$

$$b = 0.12\left(\frac{T_o}{T_\infty}\right)^{1/2}(z - z_o)$$

$$u_o = 3.4\left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3}\ \dot{Q}_c^{1/3}(z - z_o)^{-1/3}$$

$$u_o = 1.0\left(\frac{\dot{Q}_c}{z-z_o}\right)^{1/3}$$

$$\Delta T_o = 9.1\left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3}\ \dot{Q}_c^{2/3}(z - z_o)^{-5/3}$$

$$\Delta T_o = 25\left(\frac{\dot{Q}_c^{2/5}}{z-z_o}\right)^{5/3}$$

For z > L

$$\dot{m}_p = 0.071\dot{Q}_c^{1/3}(z - z_o)^{5/3} + 1.92\ \times 10^{-3}\dot{Q}_c$$

For z < L

$$\dot{m}_p = 0.0056\dot{Q}_c\frac{z}{L}$$

McCAFFREY PLUME:

$$\Delta T_o = \left(\frac{\kappa}{0.9\sqrt{2g}}\right)^2\left(\frac{z}{\dot{Q}^{2/5}}\right)^{2\eta-1}\ T_\infty$$

$$u_o = \kappa\left(\frac{z}{\dot{Q}^{2/5}}\right)^{\eta}\dot{Q}^{1/5}$$

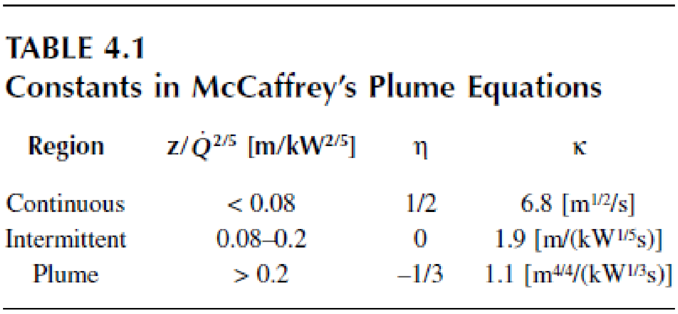

TABLE 4.1
Constants in McCaffrey's Plume Equations

Region	$z/\dot{Q}^{2/5}$ [m/kW$^{2/5}$]	η	κ
Continuous	< 0.08	1/2	6.8 [m$^{1/2}$/s]
Intermittent	0.08–0.2	0	1.9 [m/(kW$^{1/5}$s)]
Plume	> 0.2	–1/3	1.1 [m$^{4/4}$/(kW$^{1/3}$s)]

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THOMAS PLUME:

$$\dot{m}_p = 0.188 P z^{3/2}$$

$$\dot{m}_p = 0.59 D z^{3/2}$$

CEILING JET:

You and Faeth carried out experiments for this scenario and analyzed the data, resulting in the following approximate expression for the radial flame extension divided by fuel source diameter:[9]

$$\frac{r_f}{D} = 0.5\left(\frac{L-H}{D}\right)^{0.96} \qquad (4.40)$$

This is roughly equivalent to saying that the radial flame extension is equal to half the free flame height part that would extend above the ceiling, or $r_f < 0.5(L - H)$. Equation (4.40) is intended

Heskestad and Hamada[13] carried out six experiments for larger energy release rates (93–760 kW), which gave an average flame extension

$$r_f = 0.95(L - H) \qquad (4.41)$$

The constant 0.95 was an average of values in the range 0.88–1.05. Equation (4.41) may provide more realistic estimates than Eq. (4.40) for larger flames, but more experimental evidence is needed.

$$T_{max} - T_\infty = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}}$$ r/H<0.18

$$T_{max} - T_\infty = \frac{5.38\left(\dot{Q}/r\right)^{2/3}}{H}$$ r/H>0.18

$$u_{max} = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3}$$ r/H<0.15

$$u_{max} = \frac{0.195\dot{Q}^{1/3}H^{1/2}}{r^{5/6}}$$ r/H>0.15

ENCLOSURE FIRE

2 VENTS OPENING

UPPER	LOWER
$\Delta P_u = \frac{1}{2} v_g^2 \rho_g$ $v_g = \sqrt{\frac{2h_u(\rho_a - \rho_g)g}{\rho_g}}$ $\dot{m}_g = C_d A_u \rho_g \sqrt{\frac{2h_u(\rho_a - \rho_g)g}{\rho_g}}$	$\Delta P_1 = \frac{1}{2} v_a^2 \rho_a$ $v_a = \sqrt{\frac{2h_1(\rho_a - \rho_g)g}{\rho_a}}$ $\dot{m}_a = C_d A_1 \rho_a \sqrt{\frac{2h_1(\rho_a - \rho_g)g}{\rho_a}}$
Neutral Point	
$\frac{h_1}{h_u} = \left(\frac{A_u}{A_1}\right)^2 \frac{\rho_g}{\rho_a}$ $\frac{h_1}{h_u} = \left(\frac{A_u}{A_1}\right)^2 \frac{T_a}{T_g}$ $H = h_u + h_1$	

WELL MIXED (1 OPENING)

$v_g(z) = \sqrt{\frac{2z(\rho_a - \rho_g)g}{\rho_g}}$ $v_a(z) = \sqrt{\frac{2z(\rho_a - \rho_g)g}{\rho_a}}$	$\dot{m}_g = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} . h_u^{3/2}$ $\dot{m}_a = \frac{2}{3} C_d W \rho_a \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_a}} . h_1^{3/2}$
Neutral Point	
$h_1 = \frac{H_o}{1 + (\rho_a/\rho_g)^{1/3}}$	

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STRATIFIED (1 OPENING)

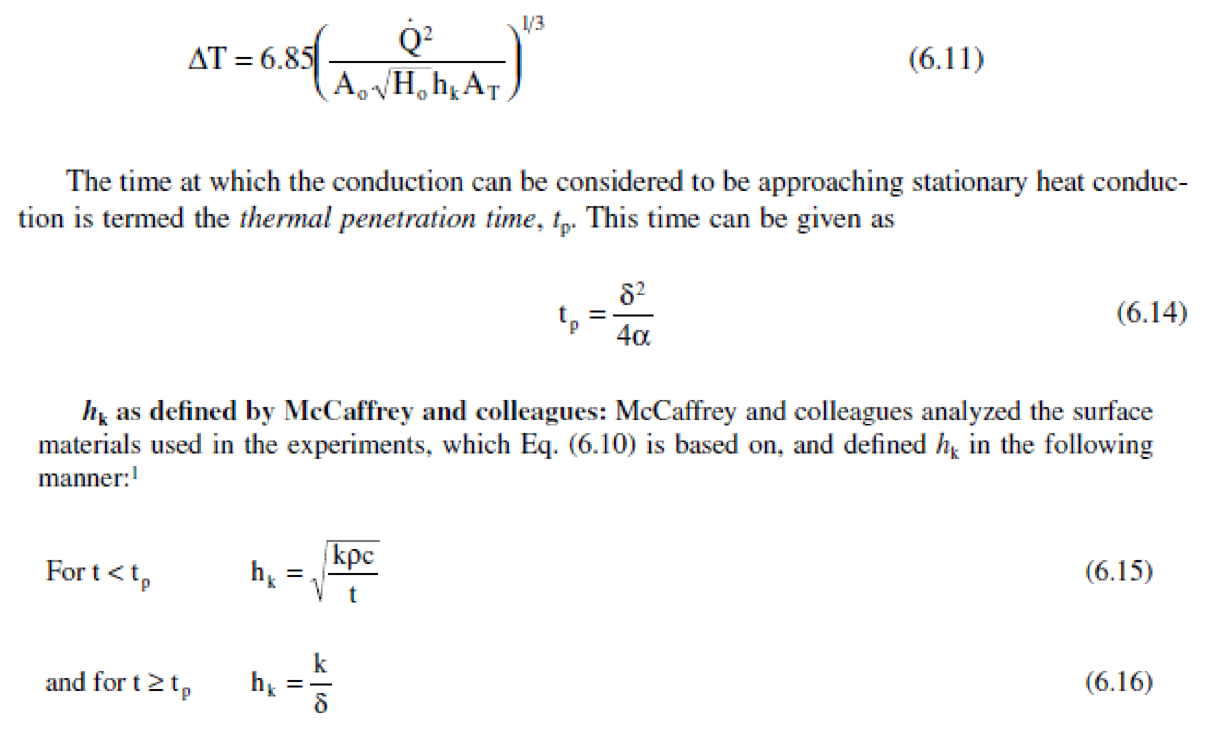
For height H_N to H_o	
$v(z)=\sqrt{\frac{2z(\rho_a-\rho_g)g}{\rho_g}}$	$\dot{m}_g=\frac{2}{3}C_dW\rho_g\sqrt{\frac{2(\rho_a-\rho_g)g}{\rho_g}}.(H_o-H_N)^{3/2}$
For height H_D to H_N	
$v_{a2}=\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$	$\dot{m}_{a2}=C_dWH_D\rho_a\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$
For height 0 to H_D	
$v_{a2}=\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$	$\dot{m}_{a2}=C_dWH_D\rho_a\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$
Total mass flow rate in through the vent	
$\dot{m}_a=\frac{2}{3}C_dW\rho_a\sqrt{\frac{2(\rho_a-\rho_g)g}{\rho_a}}.(H_N-H_D)^{1/2}\left(H_N+\frac{1}{2}H_D\right)$	

CEILING VENT

Ceilng Vent	Lower vent
$v_c=\sqrt{\frac{2(H-H_N)(\rho_a-\rho_g)g}{\rho_g}}$ $\dot{m}_c=C_dA_c\rho_g\sqrt{\frac{2(H-H_N)(\rho_a-\rho_g)g}{\rho_g}}$	$v_1=\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$ $\dot{m}_1=C_dA_1\rho_a\sqrt{\frac{2(H_N-H_D)(\rho_a-\rho_g)g}{\rho_a}}$
Neutral Point	
$H_N=\frac{A_1^2\rho_aH_D+A_c^2\rho_gH}{A_1^2\rho_a+A_c^2\rho_g}$	

TEMPERATURE:

PRE-FLASHOVER



$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}\,h_k A_T}\right)^{1/3} \qquad (6.11)$$

The time at which the conduction can be considered to be approaching stationary heat conduction is termed the *thermal penetration time*, t_p. This time can be given as

$$t_p = \frac{\delta^2}{4\alpha} \qquad (6.14)$$

h_k as defined by McCaffrey and colleagues: McCaffrey and colleagues analyzed the surface materials used in the experiments, which Eq. (6.10) is based on, and defined h_k in the following manner:[1]

For $t < t_p$ $\qquad h_k = \sqrt{\frac{k\rho c}{t}} \qquad (6.15)$

and for $t \geq t_p$ $\qquad h_k = \frac{k}{\delta} \qquad (6.16)$

TABLE 3.6
Energy Release Rate Data

Description	Growth Rate	kW/m^2 of floor area
Fire retarded treated mattress (including normal bedding)	S	17
Lightweight type C upholstered furniture[b]	M	170[a]
Moderate-weight type C upholstered furniture[b]	S	400[a]
Mail bags (full) stored 5 ft high	F	400
Cotton/polyester innerspring mattress (including bedding)	M	565[a]
Lightweight type B upholstered furniture[b]	M	680[a]
Medium-weight type C upholstered furniture[b]	S	680[a]
Methyl alcohol pool fire	UF	740
Heavyweight type C upholstered furniture[b]	S	795[a]
Polyurethane innerspring mattress (including bedding)	F	910[a]
Moderate-weight type B upholstered furniture[b]	M	1020[a]
Wooden pallets 1 1/2 feet high	M	1420
Medium-weight type B upholstered furniture[b]	M	1645[a]
Lightweight type A upholstered furniture[b]	F	1700[a]
Empty cartons 15 ft high	F	1700
Diesel oil pool fire (>about 3 ft dia.)	F	1985

TABLE 6.1
Typical Values of Thermal Properties for Some Common Materials

Material	k (W/m·K)	c (J/kg·K)	ρ (kg/m^3)	$k\rho c$ (W^{2}s/m^{4}K^2)	α (m^2/s)
Aluminium	218	890	2700	$5.2 \cdot 10^8$	$9.1 \cdot 10^{-5}$
Copper	395	385	8920	$1.4 \cdot 10^9$	$1.2 \cdot 10^{-4}$
Steel (mild)	45	460	7820	$1.6 \cdot 10^8$	$1.3 \cdot 10^{-5}$
Brick (common)	0.69	840	1600	$9.3 \cdot 10^5$	$5.2 \cdot 10^{-7}$
Concrete	0.8–1.4	880	1900–2300	$2 \cdot 10^6$	$5.7 \cdot 10^{-7}$
Lightweight concrete	0.15	1000	500	$7.5 \cdot 10^4$	$3.0 \cdot 10^{-7}$
Glass (plate)	0.8	840	2600	$1.8 \cdot 10^6$	$3.7 \cdot 10^{-7}$
Cork plates	0.08	1000	500	$4.0 \cdot 10^4$	$1.6 \cdot 10^{-7}$
Fiber insulating board	0.041	2090	229	$2.0 \cdot 10^4$	$8.6 \cdot 10^{-8}$
Gypsum plaster	0.48	840	1440	$5.8 \cdot 10^5$	$4.1 \cdot 10^{-7}$
Mineral wool, plates	0.041	800	100	$3.3 \cdot 10^3$	$5.1 \cdot 10^{-7}$

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