



**UNIVERSITI KUALA LUMPUR**  
**Malaysian Institute of Marine Engineering Technology**

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**FINAL EXAMINATION**  
**FEBRUARY 2025 SEMESTER SESSION**

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**SUBJECT CODE** : LEB11803 / LMB11603

**SUBJECT TITLE** : FUNDAMENTAL THERMODYNAMICS

**PROGRAMME NAME** : BACHELOR OF ELECTRICAL AND ELECTRONICS  
(FOR MPU: PROGRAMME LEVEL) ENGINEERING TECHNOLOGY (MARINE) &  
BET IN MARINE ENGINEERING

**TIME / DURATION** : 09.00 AM - 11.30 AM  
(2 HOURS 30 MINUTES)

**DATE** : 2 JULY 2025

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**INSTRUCTIONS TO CANDIDATES**

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1. Please read **CAREFULLY** the instructions given in the question paper.
  2. This question paper has information printed on both sides of the paper.
  3. This question paper consists of **TWO (2)** sections; Section A and Section B.
  4. Answer **ALL** question in Section A, and **THREE (3)** questions **ONLY** in Section B.
  5. Please write your answers on this answer booklet provided.
  6. Answer **ALL** questions in English language **ONLY**.
  7. Answer should be written in blue of black ink except for sketching, graphic and illustration.
  8. Thermodynamics Table of Properties and Formula has been appended for your reference.
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**THERE ARE 7 PAGES OF QUESTIONS, INCLUDING THIS PAGE.**

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## SECTION A (Total: 40 marks)

**INSTRUCTION: Answer ALL questions.**  
**Please use the answer booklet provided.**

**Question 1**

With reference to basic concept of thermodynamics to systems and processes.

(a) Define the following with related example:

- i. Adiabatic system
- ii. Closed system
- iii. Open system

(6 marks)

(b)

- i. Convert a flow rate of **2000** liters per minute into cubic meters per second ( $\text{m}^3/\text{s}$ )
- ii. A pressure gauge reads **35** psi. Convert this pressure into Pascals ( $\text{N}/\text{m}^2$ ).
- iii. The density of a substance is **0.5**  $\text{lbm}/\text{ft}^3$ . Convert this value into kilograms per cubic meter ( $\text{kg}/\text{m}^3$ ).

(6 marks)

(c) A deep-sea diver descends into a freshwater lake and experiences a gauge pressure of **30000** kPa. Given that the atmospheric pressure at the surface is **101** kPa and the density of freshwater is **1000**  $\text{kg}/\text{m}^3$ , determine the:

- i. depth (**h**) of the diver in meters.
- ii. absolute pressure, ( $P_{\text{abs}}$ ) acting on the diver in kPa

(5 marks)

(3 marks)

**Question 2**

With reference to forms of energy and energy transfer of a system.

(a) Define the following:

- i. Kinetic energy
- ii. Flow energy
- iii. Mechanical energy,

(6 marks)

(b) A piston-cylinder device containing water is being heated, causing the piston to rise. During this heating process:

- 120 kJ of heat is transferred to the water,  $Q_{in}$ .
- 15 kJ of heat is lost to the surroundings,  $Q_{out}$ .
- The vapor does 10 kJ of work as it expands,  $W_{out}$ .

Calculate the change in the **internal energy** of the water for this process.

(6 marks)

(c) A waterfall is located at a height of **80 meters (z)** above a hydroelectric power plant. Water flows over the fall with a velocity of **5 m/s (V)** and a flow rate of **400 m<sup>3</sup>/s ( $\dot{V}$ )**. Determine the:

- i. total mechanical energy ( $e_{mech}$ ) of the water at the top of the waterfall per unit mass and
- ii. the maximum theoretical power generation potential ( $\dot{E}$ ) of the falling water at that location

(2 marks)

(6 marks)

**SECTION B (Total: 60 marks)**

**INSTRUCTION: Answer only THREE questions.**

**Please use the answer booklet provided.**

**Question 3**

With reference to Laws of thermodynamics, energies, systems, pure substance properties and entropy.

(a) A closed, well-insulated vessel contains water at a pressure of **200 kPa** and a specific volume of **0.6 m<sup>3</sup>/kg**.

i. Based on the given properties, **determine the phase** of the water (compressed liquid, saturated mixture, or superheated vapor).

(3 marks)

ii. **Explain briefly** how you determined the phase using thermodynamic property tables.

(2 marks)

(b) Complete Table 1 below of thermodynamics properties for refrigerant-134a (R-134a). Show all the calculations involved. Use the following abbreviations where needed:

- CL – Compressed (Subcooled) liquid
- SL – Saturated liquid
- SM – Saturated Mixture
- SV – Saturated Vapor
- SHV – Superheated Vapor
- NA – Not applicable

Table 1: Thermodynamics properties for R-134a

| P (kPa) | T(°C) | u, kJ/kg | h, kJ/kg | Phase Description | Quality (x) |
|---------|-------|----------|----------|-------------------|-------------|
| 200     | (a)   | (b)      | 150      | (c)               | (d)         |
| (e)     | 24    | (f)      | 263.67   | (g)               | (h)         |
| (i)     | 80    | (j)      | 322.98   | (k)               | (l)         |
| 400     | - 10  | (m)      | (n)      | (o)               | NIL         |

(15 marks)

**Question 4**

With reference to Laws of thermodynamics, energies, systems, pure substance properties and entropy.

- (a) Explain the key features of a  $T$ - $v$  diagram for pure substances undergoing **constant-pressure** phase-change processes. Your answer should be **describing** the phases involved and **labeling** important points such as saturated liquid (SL), saturated mixture (SM), and saturated vapor (SV).

(5 marks)

- (b) A **400-L** rigid tank contains **5 kg** of air at **25°C**. Determine the reading on the pressure gage,  $P_{\text{gage}}$  if the atmospheric pressure,  $P_{\text{atm}}$  is **97 kPa**.

(6 marks)

- (c) A **1.5 kg** sample of water is contained in a rigid tank with a volume of **300 liters**, and the pressure is measured to be **1200 kPa**.

- i. Identify the **phase** of the water at this state.

(3 marks)

- ii. Determine the temperature,  $T$  ( $^{\circ}\text{C}$ ).

(3 marks)

- iii. Determine its internal energy,  $u$  (kJ/kg)

(3 marks)

**Question 5**

With reference to Laws of thermodynamics, energies, systems, pure substance properties and entropy.

Steam flows steadily through an adiabatic turbine. The inlet conditions of the steam are **4 Mpa** ( $P_1$ ), **500°C** ( $T_1$ ), and **80 m/s** ( $V_1$ ), and the exit conditions are **30 kPa** ( $P_2$ ), **92 percent quality** ( $x_2$ ), and **50 m/s** ( $V_2$ ). The mass flow rate of the steam is **12 kg/s** ( $\dot{m}$ ).

- (a) Explain how the change in kinetic energy of steam flowing through an adiabatic turbine can be determined based on inlet and outlet velocities. (2 marks)
- (b) Calculate the change in kinetic energy, in kJ/kg (3 marks)
- (c) the power output,  $\dot{W}_{out}$  in kW (9 marks)
- (d) the turbine inlet area,  $A_1$  in  $m^2$  (6 marks)

**Question 6**

With reference to the second law of thermodynamics to cyclic devices.

- (a) Sketch a schematic diagram of the refrigerator with complete label. (5 marks)
- (b) An air conditioner removes heat steadily from a house at a rate of **750 kJ/min ( $Q_L$ )**, while drawing electric power at a rate of **5.25 kW ( $W_{in}$ )**. Analyze the operation of this system and answer the following:
- i. Discuss how the efficiency (COP) of an air conditioner reflects its performance. (2 marks)
  - ii. Calculate the COP of this air conditioner, (2 marks)
  - iii. rate of heat transfer to the outside air,  $Q_H$  (kW). (4 marks)
- (c) A Carnot refrigerator operates in a room in which the temperature is **25°C**. The refrigerator consumes **500 W ( $W_{in}$ )** of power when operating and has a **COP of 4.5**. Determine:
- i. the rate of heat removal from the refrigerated space,  $Q_L$  and (3 marks)
  - ii. the temperature of the refrigerated space,  $T_L$  (4 marks)

**END OF EXAMINATION PAPER**

## THERMODYNAMICS FORMULAE

|   |
|---|
| <b>First Law of Thermodynamics</b>  |
| $\text{Quality, } x = \frac{m_g}{m_{total}} = \frac{v - v_f}{v_{fg}}$ $v = v_f + (x)v_{fg}; \quad u = u_f + (x)u_{fg}; \quad h = h_f + (x)h_{fg}$   |
| <p><b>Mass total,</b></p> $m_{total} = m_f + m_g$   |
| <p><b>Ideal gas equation</b></p> $PV = mRT; \quad Pv = RT$ $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$  |
| <p><b>General Energy Balance</b></p> $E_{in} - E_{out} = \Delta E_{system}$   |
| $\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$  |
| <p><b>Energy Balance for a closed system, constant volume process</b></p> $Q - W = \Delta U + \Delta KE + \Delta PE$ <p><i>Ideal gas:</i> <math>Q - W = mc_v(T_2 - T_1)</math></p>  |
| <p><b>Energy Balance for a constant pressure process</b></p> $W_b + \Delta U = \Delta H$ $Q - W_{other} = \Delta H + \Delta KE + \Delta PE$ <p><i>Ideal gas:</i> <math>Q - W = mc_p(T_2 - T_1)</math></p>   |
| <p><b>Conservation of mass and energy equations for steady-flow process</b></p> $\sum \dot{m}_{in} = \sum \dot{m}_{out}$ $\dot{Q} - \dot{W} = \sum_{out} \dot{m} [h + V^2/2 + gz] - \sum_{in} \dot{m} [h + V^2/2 + gz]$ $\dot{Q}_{in} + \dot{W}_{in} + \dot{m} \left( h_1 + \frac{V_1^2}{2} + gz_1 \right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{m} \left( h_2 + \frac{V_2^2}{2} + gz_2 \right)$ |
| <p><b>Boundary work (<math>P = \text{constant}</math>), <math>W_b = mP_0(v_2 - v_1)</math></b></p>  |
| <p><b>Boundary work (<math>T = \text{constant}</math>), <math>W_b = P_1V_1 \ln \left( \frac{V_2}{V_1} \right)</math></b></p>  |
| <p><b>Polytropic Process, <math>PV^n = C</math></b></p> <p><b>Boundary work (Polytropic), <math>W_b = \frac{P_1V_1 - P_2V_2}{1-n}</math></b></p>  |

**Mass flow rate**

$$\dot{m} = \rho AV = \rho \dot{V} = \frac{\dot{V}}{v}$$

**Volume flow rate**

$$\dot{V} = VA = \frac{\dot{m}}{\rho}$$

**Thermal efficiency of a Heat Engine**

$$\eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

**Coefficient of Performance of a Refrigerator and Heat Pump**

$$COP_R = \frac{Q_L}{W_{net,in}} = \frac{q_L}{w_{net,in}} = \frac{Q_L}{Q_H - Q_L}$$

$$COP_{HP} = \frac{Q_H}{W_{net,in}} = \frac{q_H}{w_{net,in}} = \frac{Q_H}{Q_H - Q_L}$$

**Carnot Heat Engine**

$$\eta_{th,Carnot} = \eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

**Carnot Refrigerators and Heat Pumps**

$$COP_{R,carnot} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$COP_{HP,carnot} = \frac{1}{1 - \frac{T_L}{T_H}}$$

**Isentropic Process**

$$s_2 = s_1$$

$$\left(\frac{T_2}{T_1}\right)_{s=const.} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$\left(\frac{T_2}{T_1}\right)_{s=const.} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

$$\left(\frac{P_2}{P_1}\right)_{s=const.} = \left(\frac{v_1}{v_2}\right)^k$$

$$\left(\frac{P_2}{P_1}\right)_{s=\text{const.}} = \frac{P_{r2}}{P_{r1}}$$

$$\left(\frac{v_2}{v_1}\right)_{s=\text{const.}} = \frac{v_{r2}}{v_{r1}}$$

### Power Cycles

$$\text{Compression ratio, } r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}} = \frac{V_1}{V_2} = \frac{v_1}{v_2} = \frac{v_{r1}}{v_{r2}}$$

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}} = \frac{w_{net}}{v \left(1 - \frac{1}{r}\right)}$$

### Otto Cycle

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\text{Thermal efficiency, } \eta_{th,Otto} = \frac{W_{net}}{Q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}} = \text{cold-air standard}$$

### Diesel Cycle

$$q_{in} = w_{b,out} + (u_3 - u_2) = P_2(v_3 - v_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$\text{Cutoff ratio, } r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}} \left[ \frac{r_c^k - 1}{k(r_c - 1)} \right] = \text{cold-air standard}$$

### Joule-Brayton Cycle

$$q_{in} = w_{b,out} + (u_3 - u_2) = P_2(v_3 - v_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

$$\text{Pressure ratio, } r_p = \frac{P_2}{P_1}$$

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{\frac{k-1}{k}}} = \text{cold-air standard}$$

### Rankine Cycle

$$w_{pump,in} = h_2 - h_1 = v(P_2 - P_1)$$

$$q_{in} = h_3 - h_2$$

$$w_{turb,out} = h_3 - h_4$$

$$q_{out} = h_4 - h_1$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$w_{net} = q_{in} - q_{out} = w_{turb,in} - w_{pump,in}$$

### Reheat Rankine Cycle

$$\text{Total heat input, } q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$q_{out} = h_6 - h_1$$

$$w_{turb,out} = w_{turb,I} + w_{turb,II} = (h_3 - h_4) + (h_5 - h_6)$$

### Refrigeration Cycle

$$W_{net,out} = Q_H - Q_L$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$COP_R = \frac{Q_L}{W_{net,in}} = \frac{q_L}{w_{net,in}} = \frac{Q_L}{Q_H - Q_L} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{Q_H}{W_{net,in}} = \frac{q_H}{w_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{h_2 - h_3}{h_2 - h_1}$$

$$COP_{HP} = COP_R + 1$$

# Conversion Factors

| DIMENSION   | METRIC  | METRIC/ENGLISH   |
|---|---|--|
| Acceleration  | 1 m/s <sup>2</sup> = 100 cm/s <sup>2</sup>  | 1 m/s <sup>2</sup> = 3.2808 ft/s <sup>2</sup><br>1 ft/s <sup>2</sup> = 0.3048* m/s <sup>2</sup>  |
| Area  | 1 m <sup>2</sup> = 10 <sup>4</sup> cm <sup>2</sup> = 10 <sup>6</sup> mm <sup>2</sup> = 10 <sup>-6</sup> km <sup>2</sup>   | 1 m <sup>2</sup> = 1550 in <sup>2</sup> = 10.764 ft <sup>2</sup><br>1 ft <sup>2</sup> = 144 in <sup>2</sup> = 0.09290304* m <sup>2</sup>   |
| Density   | 1 g/cm <sup>3</sup> = 1 kg/L = 1000 kg/m <sup>3</sup>   | 1 g/cm <sup>3</sup> = 62.428 lbm/ft <sup>3</sup> = 0.036127 lbm/in <sup>3</sup><br>1 lbm/in <sup>3</sup> = 1728 lbm/ft <sup>3</sup><br>1 kg/m <sup>3</sup> = 0.062428 lbm/ft <sup>3</sup>  |
| Energy, heat, work,<br>internal energy,<br>enthalpy | 1 kJ = 1000 J = 1000 N · m = 1 kPa · m <sup>3</sup><br>1 kJ/kg = 1000 m <sup>2</sup> /s <sup>2</sup><br>1 kWh = 3600 kJ<br>1 cal <sup>t</sup> = 4.184 J<br>1 IT cal <sup>t</sup> = 4.1868 J<br>1 Cal <sup>t</sup> = 4.1868 kJ | 1 kJ = 0.94782 Btu<br>1 Btu = 1.055056 kJ<br>= 5.40395 psia · ft <sup>3</sup> = 778.169 lbf · ft<br>1 Btu/lbm = 25,037 ft <sup>2</sup> /s <sup>2</sup> = 2.326* kJ/kg<br>1 kJ/kg = 0.430 Btu/lbm<br>1 kWh = 3412.14 Btu<br>1 therm = 10 <sup>5</sup> Btu = 1.055 × 10 <sup>5</sup> kJ<br>(natural gas) |
| Force   | 1 N = 1 kg · m/s <sup>2</sup> = 10 <sup>5</sup> dyne<br>1 kgf = 9.80665 N   | 1 N = 0.22481 lbf<br>1 lbf = 32.174 lbm · ft/s <sup>2</sup> = 4.44822 N  |
| Heat flux   | 1 W/cm <sup>2</sup> = 10 <sup>4</sup> W/m <sup>2</sup>  | 1 W/m <sup>2</sup> = 0.3171 Btu/h · ft <sup>2</sup>  |
| Heat transfer<br>coefficient                        | 1 W/m <sup>2</sup> · °C = 1 W/m <sup>2</sup> · K  | 1 W/m <sup>2</sup> · °C = 0.17612 Btu/h · ft <sup>2</sup> · °F   |
| Length  | 1 m = 100 cm = 1000 mm = 10 <sup>6</sup> μm<br>1 km = 1000 m  | 1 m = 39.370 in = 3.2808 ft = 1.0926 yd<br>1 ft = 12 in = 0.3048* m<br>1 mile = 5280 ft = 1.6093 km<br>1 in = 2.54* cm   |
| Mass  | 1 kg = 1000 g<br>1 metric ton = 1000 kg   | 1 kg = 2.2046226 lbm<br>1 lbm = 0.45359237* kg<br>1 ounce = 28.3495 g<br>1 slug = 32.174 lbm = 14.5939 kg<br>1 short ton = 2000 lbm = 907.1847 kg  |
| Power,<br>heat transfer rate                        | 1 W = 1 J/s<br>1 kW = 1000 W = 1.341 hp<br>1 hp <sup>t</sup> = 745.7 W  | 1 kW = 3412.14 Btu/h<br>= 737.56 lbf · ft/s<br>1 hp = 550 lbf · ft/s = 0.7068 Btu/s<br>= 42.41 Btu/min = 2544.5 Btu/h<br>= 0.74570 kW<br>1 boiler hp = 33,475 Btu/h<br>1 Btu/h = 1.055056 kJ/h<br>1 ton of refrigeration = 200 Btu/min   |
| Pressure  | 1 Pa = 1 N/m <sup>2</sup><br>1 kPa = 10 <sup>3</sup> Pa = 10 <sup>-3</sup> MPa<br>1 atm = 101.325 kPa = 1.01325 bars<br>= 760 mm Hg at 0°C<br>= 1.03323 kgf/cm <sup>2</sup><br>1 mm Hg = 0.1333 kPa                           | 1 Pa = 1.4504 × 10 <sup>-4</sup> psia<br>= 0.020886 lbf/ft <sup>2</sup><br>1 psi = 144 lbf/ft <sup>2</sup> = 6.894757 kPa<br>1 atm = 14.696 psia = 29.92 in Hg at 30°F<br>1 in Hg = 3.387 kPa  |
| Specific heat                                       | 1 kJ/kg · °C = 1 kJ/kg · K = 1 J/g · °C   | 1 Btu/lbm · °F = 4.1868 kJ/kg · °C<br>1 Btu/lbmol · R = 4.1868 kJ/kmol · K<br>1 kJ/kg · °C = 0.23885 Btu/lbm · °F<br>= 0.23885 Btu/lbm · R   |

\*Exact conversion factor between metric and English units.

†Calorie is originally defined as the amount of heat needed to raise the temperature of 1 g of water by 1°C, but it varies with temperature. The international steam table (IT) calorie (generally preferred by engineers) is exactly 4.1868 J by definition and corresponds to the specific heat of water at 15°C. The thermochemical calorie (generally preferred by physicists) is exactly 4.184 J by definition and corresponds to the specific heat of water at room temperature. The difference between the two is about 0.06 percent, which is negligible. The capitalized Calorie used by nutritionists is actually a kilocalorie (1000 IT calories).

| DIMENSION            | METRIC  | METRIC/ENGLISH  |
|----------------------|---|---|
| Specific volume      | $1 \text{ m}^3/\text{kg} = 1000 \text{ L}/\text{kg} = 1000 \text{ cm}^3/\text{g}$                 | $1 \text{ m}^3/\text{kg} = 16.02 \text{ ft}^3/\text{lbm}$<br>$1 \text{ ft}^3/\text{lbm} = 0.062428 \text{ m}^3/\text{kg}$   |
| Temperature          | $T(\text{K}) = T(^{\circ}\text{C}) + 273.15$<br>$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C})$ | $T(\text{R}) = T(^{\circ}\text{F}) + 459.67 = 1.8T(\text{K})$<br>$T(^{\circ}\text{F}) = 1.8 T(^{\circ}\text{C}) + 32$<br>$\Delta T(^{\circ}\text{F}) = \Delta T(\text{R}) = 1.8 \Delta T(\text{K})$   |
| Thermal conductivity | $1 \text{ W}/\text{m} \cdot ^{\circ}\text{C} = 1 \text{ W}/\text{m} \cdot \text{K}$               | $1 \text{ W}/\text{m} \cdot ^{\circ}\text{C} = 0.57782 \text{ Btu}/\text{h} \cdot \text{ft} \cdot ^{\circ}\text{F}$   |
| Velocity             | $1 \text{ m}/\text{s} = 3.60 \text{ km}/\text{h}$   | $1 \text{ m}/\text{s} = 3.2808 \text{ ft}/\text{s} = 2.237 \text{ mi}/\text{h}$<br>$1 \text{ mi}/\text{h} = 1.46667 \text{ ft}/\text{s}$<br>$1 \text{ mi}/\text{h} = 1.6093 \text{ km}/\text{h}$  |
| Volume               | $1 \text{ m}^3 = 1000 \text{ L} = 10^6 \text{ cm}^3 (\text{cc})$                                  | $1 \text{ m}^3 = 6.1024 \times 10^4 \text{ in}^3 = 35.315 \text{ ft}^3$<br>$= 264.17 \text{ gal (U.S.)}$<br>$1 \text{ U.S. gallon} = 231 \text{ in}^3 = 3.7854 \text{ L}$<br>$1 \text{ fl ounce} = 29.5735 \text{ cm}^3 = 0.0295735 \text{ L}$<br>$1 \text{ U.S. gallon} = 128 \text{ fl ounces}$ |
| Volume flow rate     | $1 \text{ m}^3/\text{s} = 60,000 \text{ L}/\text{min} = 10^6 \text{ cm}^3/\text{s}$               | $1 \text{ m}^3/\text{s} = 15,850 \text{ gal}/\text{min (gpm)} = 35.315 \text{ ft}^3/\text{s}$<br>$= 2118.9 \text{ ft}^3/\text{min (cfm)}$   |

\*Mechanical horsepower. The electrical horsepower is taken to be exactly 746 W.

### Some Physical Constants

|  |  |
|--|--|
| Universal gas constant                     | $R_u = 8.31447 \text{ kJ}/\text{kmol} \cdot \text{K}$<br>$= 8.31447 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K}$<br>$= 0.0831447 \text{ bar} \cdot \text{m}^3/\text{kmol} \cdot \text{K}$<br>$= 82.05 \text{ L} \cdot \text{atm}/\text{kmol} \cdot \text{K}$<br>$= 1.9858 \text{ Btu}/\text{lbmol} \cdot \text{R}$<br>$= 1545.37 \text{ ft} \cdot \text{lb}/\text{lbmol} \cdot \text{R}$<br>$= 10.73 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R}$ |
| Standard acceleration of gravity           | $g = 9.80665 \text{ m}/\text{s}^2$<br>$= 32.174 \text{ ft}/\text{s}^2$   |
| Standard atmospheric pressure              | $1 \text{ atm} = 101.325 \text{ kPa}$<br>$= 1.01325 \text{ bar}$<br>$= 14.696 \text{ psia}$<br>$= 760 \text{ mm Hg (0}^{\circ}\text{C)}$<br>$= 29.9213 \text{ in Hg (32}^{\circ}\text{F)}$<br>$= 10.3323 \text{ m H}_2\text{O (4}^{\circ}\text{C)}$  |
| Stefan-Boltzmann constant                  | $\sigma = 5.6704 \times 10^{-8} \text{ W}/\text{m}^2 \cdot \text{K}^4$<br>$= 0.1714 \times 10^{-8} \text{ Btu}/\text{h} \cdot \text{ft}^2 \cdot \text{R}^4$  |
| Boltzmann's constant                       | $k = 1.380650 \times 10^{-23} \text{ J}/\text{K}$  |
| Speed of light in vacuum                   | $c_0 = 2.9979 \times 10^8 \text{ m}/\text{s}$<br>$= 9.836 \times 10^8 \text{ ft}/\text{s}$   |
| Speed of sound in dry air at 0°C and 1 atm | $c = 331.36 \text{ m}/\text{s}$<br>$= 1089 \text{ ft}/\text{s}$  |
| Heat of fusion of water at 1 atm           | $h_{if} = 333.7 \text{ kJ}/\text{kg}$<br>$= 143.5 \text{ Btu}/\text{lbm}$  |
| Enthalpy of vaporization of water at 1 atm | $h_{fg} = 2256.5 \text{ kJ}/\text{kg}$<br>$= 970.12 \text{ Btu}/\text{lbm}$  |