

**2.1**

Situation: A system is separated from its surrounding by a

- a. border
- b. divisor
- c. boundary
- d. fractionation line

**SOLUTION**

Answer is (c) boundary. See definition in EFM11e §2.1.

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## 2.2

Find:

Where in this text can you find:

- density data for such liquids as oil and mercury?
- specific weight data for air (at standard atmospheric pressure) at different temperatures?
- specific gravity data for sea water and kerosene?

## SOLUTION

- Density data for liquids other than water can be found in Table A.4 in EFM11e. Temperatures are specified.
- Data for several properties of air (at standard atmospheric pressure) at different temperatures are in Table A.3 in EFM11e.
- Specific gravity and other data for liquids other than water can be found in Table A.4 in EFM11e. Temperatures are specified.

### 2.3

Situation:

Regarding water and seawater:

- Which is more dense, seawater or freshwater?
- Find (SI units) the density of seawater (10°C, 3.3% salinity).
- Find the same in traditional units.
- What pressure is specified for the values in (b) and (c)?

### SOLUTION

- Seawater is more dense, because of the weight of the dissolved salt.
- The density of seawater (10°C, 3.3% salinity) in SI units is 1026 kg/m<sup>3</sup>, see Table A.3 in EFM11e.
- The density of seawater (10°C, 3.3% salinity) in traditional units is 1.99 slugs/ft<sup>3</sup>, see Table A.3 in EFM11e.
- The specified pressure for the values in (b) and (c) is standard atmospheric pressure; as stated in the title of Table A.3 in EFM11e.

## 2.4

### Situation:

Where in this text can you find:

- a. values of surface tension ( $\sigma$ ) for kerosene and mercury?
- b. values for the vapor pressure ( $p_v$ ) of water as a function of temperature?

### **SOLUTION**

- a. Table A.4 (EFM11e). Note that these values of surface tension assume a liquid/air interface.
- b. Table A.5 (EFM11e). Note that vapor pressure tables are always in absolute pressure; since  $p_v$  is a material property, it can't be documented for gage pressures because gage pressures vary from day to day, and from place to place.

## 2.5

### Situation:

Open tank of water.

$$T_{20} = 20^\circ\text{C}, T_{80} = 80^\circ\text{C}.$$

$$V = 500 \text{ L}, d = 2 \text{ m}.$$

### Find:

Percentage change in volume.

Water level rise for given diameter.

### Properties:

From Table A.5 (EFM11e):  $\rho_{20} = 998 \frac{\text{kg}}{\text{m}^3}$ , and  $\rho_{80} = 972 \frac{\text{kg}}{\text{m}^3}$ .

## PLAN

Density changes as a function of temperature. For a given system (mass = constant):

- Find the mass for a known density and volume
- Use geometry to get water level change

## SOLUTION

a. Calculate percentage change in volume for this mass of water at two temperatures. For the first temperature, the volume is given as  $V_{20} = 500 \text{ L} = 0.5 \text{ m}^3$ . Its density is  $\rho_{20} = 998 \frac{\text{kg}}{\text{m}^3}$ . Therefore, the mass for both cases is given by.

$$\begin{aligned} m &= 998 \frac{\text{kg}}{\text{m}^3} \times 0.5 \text{ m}^3 \\ &= 499.0 \text{ kg} \end{aligned}$$

For the second temperature, that mass takes up a larger volume:

$$\begin{aligned} V_{80} &= \frac{m}{\rho} = \frac{499.0 \text{ kg}}{972 \frac{\text{kg}}{\text{m}^3}} \\ &= 0.513 \text{ m}^3 \end{aligned}$$

Therefore, the percentage change in volume is

$$\frac{0.513 \text{ m}^3 - 0.5 \text{ m}^3}{0.5 \text{ m}^3} = 0.0267$$

volume % change = 2.7%

b. If the tank has  $D = 2 \text{ m}$ , then  $V = \pi r^2 h = 3.14h$ . Therefore:

$$h_{20} = 0.159 \text{ m}$$

$$h_{80} = 0.163 \text{ m}$$

water level rise is  $0.163 - 0.159 \text{ m} = 0.004257 \text{ m} = 4.26 \text{ mm}$

## REVIEW

Density changes can result from temperature changes, as well as pressure changes.

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**2.6**

Situation:

If the density,  $\rho$ , of air increases by a factor of 1.4x due to a temperature change,

- a. specific weight increases by 1.4x
- b. specific weight increases by 13.7x
- c. specific weight remains the same

**SOLUTION**

Since specific weight is the product  $\rho g$ , if  $\rho$  increases by a factor of 1.4, then specific weight increases by 1.4 times as well. The answer is (a).

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**2.7**

Situation:

The following questions relate to viscosity.

Find:

- (a) The primary dimensions of viscosity and five common units of viscosity.
- (b) The viscosity of motor oil (in traditional units).

**SOLUTION**

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a) Primary dimensions of viscosity are  $\left[\frac{M}{LT}\right]$ .

Five common units are:

i) $\frac{\text{N}\cdot\text{s}}{\text{m}^2}$ ; ii) $\frac{\text{dyn}\cdot\text{s}}{\text{cm}^2}$ ; iii) poise; iv) centipoise; and v) $\frac{\text{lb}\cdot\text{s}}{\text{ft}^2}$
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(b) To find the viscosity of SAE 10W-30 motor oil at 115 °F, there are no tabular data in the text. Therefore, one should use Figure A.2 (EFM11e). For traditional units (because the temperature is given in Fahrenheit) one uses the left-hand axis to report that  $\mu = 1.2 \times 10^{-3} \frac{\text{lb}\cdot\text{s}}{\text{ft}^2}$ .

Note: one should be careful to identify the correct factor of 10 for the log cycle that contains the correct data point. For example, in this problem, the answer is between  $1 \times 10^{-3}$  and  $1 \times 10^{-2}$ . Therefore the answer is  $1.2 \times 10^{-3}$  and not  $1 \times 10^{-2}$ .

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**2.8**

Situation:

When looking up values for density, absolute viscosity, and kinematic viscosity, which statement is most true for BOTH liquids and gases?

- a. all 3 of these properties vary with temperature
- b. all 3 of these properties vary with pressure
- c. all 3 of these properties vary with temperature and pressure

**SOLUTION**

Best answer is (a). The absolute viscosities of liquids and gases do not vary with pressure.

Answer (c) is also acceptable, because kinematic viscosity does vary with pressure (because density does).

**2.9**

Situation:

Kinematic viscosity (select all that apply)

- a. is another name for absolute viscosity
- b. is viscosity/density
- c. is dimensionless because forces are canceled out
- d. has dimensions of  $L^2/T$

**SOLUTION**

The answers are (b) and (d).

## 2.10

### Situation:

Change in viscosity and density due to temperature.

$$T_1 = 10^\circ\text{C}, T_2 = 90^\circ\text{C}.$$

$$p_{atm} = 101 \text{ kN/m}^2 \text{ (standard atmospheric pressure)}$$

### Find:

Change in viscosity and density of water.

Change in viscosity and density of air.

### Properties:

See Plan, below.

## PLAN

Use tabular data; use subtraction to calculate changes in property values.

For water, use data from Table A.5 (EFM11e). For air, use data from Table A.3 (EFM11e).

## SOLUTION

Changes in viscosity and density of water

$$\mu_{90} = 3.15 \times 10^{-4} \text{ N} \cdot \text{s/m}^2$$

$$\mu_{10} = 1.31 \times 10^{-3} \text{ N} \cdot \text{s/m}^2$$

$$\Delta\mu = -9.95 \times 10^{-4} \text{ N} \cdot \text{s/m}^2$$

$$\rho_{90} = 965 \text{ kg/m}^3$$

$$\rho_{10} = 1000 \text{ kg/m}^3$$

$$\Delta\rho = -35 \text{ kg/m}^3$$

Changes in viscosity and density of air

$$\mu_{90} = 2.13 \times 10^{-5} \text{ N} \cdot \text{s/m}^2$$

$$\mu_{10} = 1.76 \times 10^{-5} \text{ N} \cdot \text{s/m}^2$$

$$\Delta\mu = 3.70 \times 10^{-6} \text{ N} \cdot \text{s/m}^2$$

$$\rho_{90} = 0.97 \text{ kg/m}^3$$

$$\rho_{10} = 1.25 \text{ kg/m}^3$$

$$\Delta\rho = -0.28 \text{ kg/m}^3$$

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### 2.11

Situation:

Air at certain temperatures.

$$T_1 = 10^\circ\text{C}, T_2 = 50^\circ\text{C}.$$

Find:

Change in kinematic viscosity.

Properties:

From Table A.3 (EFM11e),  $\nu_{50} = 1.79 \times 10^{-5} \text{ m}^2/\text{s}$ ,  $\nu_{10} = 1.41 \times 10^{-5} \text{ m}^2/\text{s}$ .

### PLAN

Use properties found in Table A.3 (EFM11e).

### SOLUTION

$$\Delta \nu_{\text{air}, 10 \rightarrow 50} = (1.79 - 1.41) \times 10^{-5}$$
$$\Delta \nu_{\text{air}, 10 \rightarrow 50} = 3.8 \times 10^{-6} \text{ m}^2/\text{s}$$

## 2.12

### Situation:

Viscosity of SAE 10W-30 oil, kerosene and water.

$$T = 50^\circ\text{C}$$

### Find:

Dynamic and kinematic viscosity of each fluid.

### PLAN

Use property data found in Fig. A.2, Fig. A.2, and Table A.5 (all in EFM11e).

### SOLUTION

	Oil (SAE 10W-30)	kerosene	water
$\mu(\text{N} \cdot \text{s}/\text{m}^2)$	$4.0 \times 10^{-2}$ (Fig. A-2)	$1.0 \times 10^{-3}$ (Fig. A-2)	$5.47 \times 10^{-4}$ Table A.5
$\nu(\text{m}^2/\text{s})$	$4.5 \times 10^{-5}$ (Fig. A-3)	$1.5 \times 10^{-6}$ (Fig. A-3)	$5.53 \times 10^{-7}$ Table A.5

### Note to instructor:

Expect only accuracy to 1 significant figure on the oil and kerosene data, because of difficulty interpolating on a log-scale figure. Students should, however, be able to report the correct order of magnitude (power of 10) for the 2 forms of viscosity for these 2 fluids.

## 2.13

### Situation:

Comparing properties of air and water at standard atmospheric pressure

### Find:

Ratio of dynamic viscosity of air to that of water.

Ratio of kinematic viscosity of air to that of water.

### Properties:

Air (20°C, 1 atm), Table A.3 (EFM11e),  $\mu = 1.81 \times 10^{-5} \text{ N}\cdot\text{s}/\text{m}^2$ ;  $\nu = 1.51 \times 10^{-5} \text{ m}^2/\text{s}$

Water (20°C, 1 atm), Table A.5 (EFM11e),  $\mu = 1.00 \times 10^{-3} \text{ N}\cdot\text{s}/\text{m}^2$ ;  $\nu = 1.00 \times 10^{-6} \text{ m}^2/\text{s}$

## SOLUTION

Dynamic viscosity

$$\frac{\mu_{\text{air}}}{\mu_{\text{water}}} = \frac{1.81 \times 10^{-5} \text{ N} \cdot \text{s} / \text{m}^2}{1.00 \times 10^{-3} \text{ N} \cdot \text{s} / \text{m}^2}$$

$$\frac{\mu_{\text{air}}}{\mu_{\text{water}}} = 1.81 \times 10^{-2}$$

Kinematic viscosity

$$\frac{\nu_{\text{air}}}{\nu_{\text{water}}} = \frac{1.51 \times 10^{-5} \text{ m}^2 / \text{s}}{1.00 \times 10^{-6} \text{ m}^2 / \text{s}}$$

$$\frac{\nu_{\text{air}}}{\nu_{\text{water}}} = 15.1$$

## REVIEW

1. Water at these conditions (liquid) is about 55 times more viscous than air (gas).
2. However, the corresponding kinematic viscosity of air is 15 times higher than the kinematic viscosity of water. The reason is that kinematic viscosity includes density and  $\rho_{\text{air}} \ll \rho_{\text{water}}$ .
3. Remember that
  - (a) kinematic viscosity ( $\nu$ ) is related to dynamic viscosity ( $\mu$ ) by:  $\nu = \mu/\rho$ .
  - (b) the labels "viscosity," "dynamic viscosity," and "absolute viscosity" are synonyms.

## 2.14

### Situation:

Properties of air and water.

$$T = 40^\circ\text{C}, p = 170 \text{ kPa}.$$

### Find:

Kinematic and dynamic viscosities of air and water.

### Properties:

Air data from Table A.3 (EFM11e),  $\mu_{\text{air}} = 1.91 \times 10^{-5} \text{ N}\cdot\text{s}/\text{m}^2$

Water data from Table A.5 (EFM11e),  $\mu_{\text{water}} = 6.53 \times 10^{-4} \text{ N}\cdot\text{s}/\text{m}^2$ ,  $\rho_{\text{water}} = 992 \text{ kg}/\text{m}^3$ .

## PLAN

Apply the ideal gas law to find density. Find kinematic viscosity as the ratio of dynamic and absolute viscosity.

## SOLUTION

A.) Air

Ideal gas law

$$\begin{aligned}\rho_{\text{air}} &= \frac{p}{RT} \\ &= \frac{170,000 \text{ Pa}}{(287 \text{ J/kg K})(313.2 \text{ K})} \\ &= 1.89 \text{ kg}/\text{m}^3\end{aligned}$$

$$\mu_{\text{air}} = 1.91 \times 10^{-5} \frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

$$\begin{aligned}\nu &= \frac{\mu}{\rho} \\ &= \frac{1.91 \times 10^{-5} \text{ N s}/\text{m}^2}{1.89 \text{ kg}/\text{m}^3}\end{aligned}$$

$$\nu_{\text{air}} = 10.1 \times 10^{-5} \text{ m}^2/\text{s}$$

B.) water

$$\mu_{\text{water}} = 6.53 \times 10^{-5} \text{ N}\cdot\text{s}/\text{m}^2$$

$$\begin{aligned}\nu &= \frac{\mu}{\rho} \\ \nu &= \frac{6.53 \times 10^{-4} \text{ N s}/\text{m}^2}{992 \text{ kg}/\text{m}^3}\end{aligned}$$

$$\nu_{\text{water}} = 6.58 \times 10^{-7} \text{ m}^2/\text{s}$$

**2.15**

Situation:

Oxygen at 50 °F and 100 °F.

Find:

Ratio of viscosities:  $\frac{\mu_{100}}{\mu_{50}}$ .

**SOLUTION**

Because the viscosity of gases increases with temperature  $\mu_{100}/\mu_{50} > 1$ . Correct choice is **(c)**.

**2.16**

Situation:

Specific gravity (select all that apply)

- a. can have units of  $\text{N/m}^3$
- b. is dimensionless
- c. increases with temperature
- d. decreases with temperature

**SOLUTION**

Correct answers are b and d. Specific gravity is a ratio of the density of some liquid divided by the density of water at  $4^\circ\text{C}$ . Therefore it is dimensionless. As temperature goes up, the density of the liquid in the numerator decreases, but the denominator stays the same. Therefore the  $SG$  decreases as temperature increases. See Table 2.2 in §2.2 of EFM11e.

**2.17**

Situation:

If a liquid has a specific gravity of 1.7,

- a) What is the density in slugs per cubic feet?
- b) What is the specific weight in pounds force per cubic feet?

**SOLUTION**

$$\begin{aligned} SG &= 1.7 \\ SG &= \frac{\rho_l}{\rho_{water,4C}} \end{aligned}$$

a)

$$\begin{aligned} \rho_l &= 1.7 \left( 1.94 \frac{\text{slug}}{\text{ft}^3} \right) \\ \rho_l &= \boxed{3.3 \frac{\text{slug}}{\text{ft}^3}} \end{aligned}$$

b)

$$32.17 \text{ lbm} = 1 \text{ slug}$$

Therefore

$$\gamma = \frac{\rho}{g} = \left( \frac{3.3 \text{ slug}}{\text{ft}^3} \right) \left( \frac{32.17 \text{ lbm}}{1 \text{ slug}} \right) = \boxed{106 \frac{\text{lbf}}{\text{ft}^3}}$$

**2.18**

Situation:

What are SG,  $\gamma$ , and  $\rho$  for mercury?

State your answers in SI units and in traditional units.

**SOLUTION**

From table A.4 (EFM11e)

	SI	Traditional
SG	13.55	13.55
$\gamma$	133,000 N/m <sup>3</sup>	847 lbf/ft <sup>3</sup>
$\rho$	13,550 kg/m <sup>3</sup>	26.3 slug/ft <sup>3</sup>

**2.19**

Situation:

If you have a bulk modulus of elasticity that is a very large number, then a small change in pressure would cause

- a. a very large change in volume
- b. a very small change in volume

**SOLUTION**

Examination of Eq. 2.4 in §2.3 EFM11e shows that the answer is b.

**2.20**

Situation:

Dimensions of the bulk modulus of elasticity are

- a. the same as the dimensions of pressure/density
- b. the same as the dimensions of pressure/volume
- c. the same as the dimensions of pressure

**SOLUTION**

Examination of Eq. 2.4 in §2.3 EFM11e shows that the answer is c.

The volume units in the denominator cancel, and the remaining units are pressure.

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**2.21**

Situation:

Bulk modulus of elasticity of ethyl alcohol and water.

$$E_{ethyl} = 1.06 \times 10^9 \text{ Pa.}$$

$$E_{water} = 2.15 \times 10^9 \text{ Pa.}$$

Find:

Which substance is easier to compress?

- a. ethyl alcohol
- b. water

**PLAN**

Use bulk modulus of elasticity equation.

**SOLUTION**

The bulk modulus of elasticity is given by:

$$E = -\Delta p \frac{V}{\Delta V} = \frac{\Delta p}{d\rho/\rho}$$

This means that bulk modulus of elasticity is inversely related to change in density, and to the negative change in volume.

Therefore, the liquid with the smaller bulk modulus is easier to compress.

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Correct answer is a. Ethyl alcohol is easier to compress because it has the smaller bulk modulus of elasticity. Bulk modulus of elasticity is inversely related to change in density.

**2.22**

Situation:

Pressure is applied to a mass of water.

$$V = 4300 \text{ cm}^3, p = 4 \times 10^6 \text{ N/m}^2.$$

Find:

Volume after pressure applied ( $\text{cm}^3$ ).

Properties:

From Table A.5 (EFM11e),  $E = 2.2 \times 10^9 \text{ Pa}$

**PLAN**

1. Use modulus of elasticity equation to calculate volume change resulting from pressure change.
2. Calculate final volume based on original volume and volume change.

**SOLUTION**

1. Elasticity equation

$$\begin{aligned} E &= -\Delta p \frac{V}{\Delta V} \\ \Delta V &= -\frac{\Delta p}{E} V \\ &= -\left[ \frac{(4 \times 10^6) \text{ Pa}}{(2.2 \times 10^9) \text{ Pa}} \right] 4300 \text{ cm}^3 \\ &= -7.82 \text{ cm}^3 \end{aligned}$$

2. Final volume

$$\begin{aligned} V_{final} &= V + \Delta V \\ &= (4300 - 7.82) \text{ cm}^3 \end{aligned}$$

$$\boxed{V_{final} = 4290 \text{ cm}^3}$$

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**2.23**

Situation:

Liquid fresh water is subjected to an increase in pressure.

Find:

Pressure increase needed to reduce volume by 3%.

Properties:

From Table A.5 (EFM11e),  $E = 2.2 \times 10^9 \text{ Pa}$ .

**PLAN**

Use modulus of elasticity equation to calculate pressure change required to achieve the desired volume change.

**SOLUTION**

Modulus of elasticity equation

$$\begin{aligned} E &= -\Delta p \frac{V}{\Delta V} \\ \Delta p &= E \frac{\Delta V}{V} \\ &= -(2.2 \times 10^9 \text{ Pa}) \left( \frac{-0.03 \times V}{V} \right) \\ &= (2.2 \times 10^9 \text{ Pa}) (0.03) \\ &= 6.6 \times 10^7 \text{ Pa} \end{aligned}$$

$$\boxed{\Delta p = 66 \text{ MPa}}$$

**2.24**

Situation:

Shear stress has dimensions of

- a. force/area
- b. dimensionless

**SOLUTION**

The answer is (a). See Eq. 2.9 in EFM11e, and discussion.

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**2.25**

Situation:

The term  $dV/dy$ , the velocity gradient

- a. has dimensions of  $L/T$
- b. has dimensions of  $T^{-1}$

**SOLUTION**

$$\left[ \frac{dV}{dy} \right] = \frac{L}{T} \times \frac{1}{L} = \frac{1}{T}$$
$$\left[ \frac{dV}{dy} \right] = T^{-1}$$

Therefore the answer is (b);  $\frac{dV}{dy}$  has dimensions of  $T^{-1}$

**2.26**

Situation:

For the velocity gradient  $dV/dy$

- a. The coordinate axis for  $dy$  is parallel to velocity
- b. The coordinate axis for  $dy$  is perpendicular to velocity

**SOLUTION**

The answer is (b). See Fig. 2.12 in EFM11e, and related discussion.

**2.27**

Situation:

The no-slip condition

- a. only applies to ideal flow
- b. only applies to rough surfaces
- c. means velocity,  $V$ , is zero at the wall
- d. means velocity,  $V$ , is the velocity of the wall

**SOLUTION**

The answer is (d); velocity,  $V$ , is the velocity of the wall.

**2.28**

Situation:

Common Newtonian fluids are:

- a. toothpaste, catsup, and paint
- b. water, oil and mercury
- c. all of the above

**SOLUTION**

The answer is (b). Toothpaste, catsup, and paint are not Newtonian, but are shear-thinning; see Fig. 2.14 in EFM11e.

**2.29**

Situation:

Which of these materials will flow (deform) with even a small shear stress applied?

- a. a Bingham plastic
- b. a Newtonian fluid

**SOLUTION**

The answer is (b); see Fig. 2.14 in EFM11e.

**2.30**

Situation:

At a point in a flowing fluid, the shear stress,  $\tau$ , is  $3 \times 10^{-4}$  psi, and the velocity gradient is  $1 \text{ s}^{-1}$ .

Find:

- What is the viscosity in traditional units (in lbf, in<sup>2</sup>, and s)?
- Convert this viscosity to standard SI units.
- Is this fluid more, or less, viscous than water?

**SOLUTION**

a.

$$\begin{aligned}\tau &= \mu \frac{dV}{dy} \\ \mu &= \frac{\tau}{dV/dy} = \left( \frac{3 \times 10^{-4} \text{ lbf}}{\text{in}^2} \right) \left( \frac{\text{s}}{1} \right) \\ \mu &= \boxed{3 \times 10^{-4} \frac{\text{lbf} \cdot \text{s}}{\text{in}^2}} \text{ or } \mu = \boxed{4.32 \times 10^{-2} \frac{\text{lbf} \cdot \text{s}}{\text{ft}^2}}\end{aligned}$$

b. Convert to SI units, using grid method

$$\begin{aligned}\mu &= \left( \frac{3 \times 10^{-4} \text{ lbf} \cdot \text{s}}{\text{in}^2} \right) \left( \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right) \left( \frac{(3.281)^2 \text{ ft}^2}{1 \text{ m}^2} \right) \left( \frac{4.448 \text{ N}}{1 \text{ lbf}} \right) \\ \mu &= \boxed{2.069 \frac{\text{N} \cdot \text{s}}{\text{m}^2}}\end{aligned}$$

c. The fluid is more viscous than water, based upon a comparison to tabulated values for water. The viscosity of water ranges from  $2.8 \times 10^{-4}$  to  $1.8 \times 10^{-3} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$  depending upon temperature (Table A.5, EFM11e).