***5-36** A blackened plate is exposed to the sun so that a constant heat flux of 800 W/m2 is absorbed. The back side of the plate is insulated so that all the energy absorbed is dissipated to an airstream that blows across the plate at conditions of 25◦C, 1 atm, and 3 m/s. The plate is 25 cm square. Estimate the average temperature of the plate. What is the plate temperature at the trailing edge?

Evaluate properties at 350 K $\nu = 20.76\times10^{-6}$ $k = 0.03003$

$\Pr = 0.697$ $\mathrm{Re}_L = \dfrac{(3)(0.25)}{20.76\times10^{-6}} = 36{,}127$

$$\overline{T_w - T_\infty} = \frac{q_w L/k}{0.6795\,\mathrm{Re}_L^{1/2}\,\Pr^{1/3}} = \frac{(800)(0.25)/0.03003}{(36{,}127)^{1/2}(0.697)^{1/3}(0.6795)} = 58.16°\mathrm{C}$$

$\overline{T_w} = 25 + 58.16 = 83.16°\mathrm{C}$ Average wall temperature

at $x = 25$ cm

$$h = \frac{k}{x}0.453\,\mathrm{Re}_x^{1/2}\,\Pr^{1/3} = \frac{0.03003}{0.25}(0.453)(36{,}127)^{1/2}(0.697)^{1/3} = 9.17\ \frac{\mathrm{W}}{\mathrm{m}^2\cdot°\mathrm{C}}$$

or $\mathrm{Nu}_x = 76.34$

$$T_w - T_\infty = \frac{q_w x}{k\,\mathrm{Nu}_x} = \frac{(800)(0.25)}{(0.03003)(76.34)} = 87.24°\mathrm{C}$$

$T_w = 87.24 + 25 = 112.24°\mathrm{C}$ Temperature at the training edge

5-74 Water flows in a 2.5-cm-diameter pipe so that the Reynolds number based on diameter is 1500 (laminar flow is assumed).The average bulk temperature is 35◦C. Calculate the maximum water velocity in the tube. (Recall that *um* =0.5u0.) What would the heat transfer coefficient be for such a system if the tube wall was subjected to a constant heat flux and the velocity and temperature profiles were completely developed? Evaluate properties at bulk temperature.

$$Nu_D = \frac{hD}{k} = 4.364$$

$$h = 4.364 * \frac{k}{d}$$

$$\mathrm{Re} = 1500 = \frac{\rho u_m d}{\mu} \qquad T = 35°\mathrm{C} \qquad d = 0.025\ \mathrm{m}$$

$$\rho = 993\ \mathrm{kg/m^3} \qquad \mu = 7.24 \times 10^{-4} \qquad k = 0.627$$

$$u_m = \frac{(1500)(7.24 \times 10^{-4})}{(993)(0.025)} = 0.0437\ \mathrm{m/sec}$$

$$u_0 = 2u_m = 0.0875\ \mathrm{m/sec}$$

$$h = \frac{(4.364)(0.627)}{0.025} = 109.4\ \frac{\mathrm{W}}{\mathrm{m^2 \cdot °C}}$$

5-81 Glycerin at 30◦C flows past a 30-cm-square flat plate at a velocity of 1.5 m/s. The drag force is measured as 8.9 N (both sides of the plate). Calculate the heat-transfer coefficient for such a flow system.

$$St\, Pr^{2/3} = \frac{Cf}{2}$$

$$\overline{\tau_w} = \overline{C_f}\frac{\rho u_\infty^2}{2}$$

$$\overline{C_f} = \frac{\overline{\tau_w} * 2}{\rho u_\infty^2}$$

$$T_\infty = 30°\mathrm{C} = 303\ \mathrm{K} \qquad \rho = 1258 \qquad L = 0.3\ \mathrm{m} \qquad c_p = 2445$$

$$u_\infty = 1.5\ \mathrm{m/sec} \qquad \mathrm{Pr} = 5380 \qquad D = 8.9N = \tau_w A\ \text{(both sides)}$$

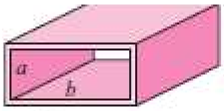
$$\tau_w = \frac{8.9}{2(0.3)^2} = 49.44\ \mathrm{N/m^2} \qquad C_f = \frac{(2)(49.44)}{(1258)(1.5)^2} = 0.0349$$

$$\mathrm{St\,Pr}^{2/3} = \frac{C_f}{2} \qquad \mathrm{St} = \frac{0.0349}{2}(5380)^{-2/3} = 5.689 \times 10^{-5}$$

$$\bar{h} = (5.689 \times 10^{-5})(1258)(1.5)(2445) = 262\ \frac{\mathrm{W}}{\mathrm{m^2 \cdot °C}}$$

6-5 Water flows in a duct having a cross section 5 × 10 mm with a mean bulk temperature of 20◦C. If the duct wall temperature is constant at 60◦C and fully developed laminar flow is experienced, calculate the heat transfer per unit length.

Rectangular duct:



$$D_h = \frac{4ab}{2(a+b)} = \frac{2ab}{a+b}$$

$Nu_D = \frac{hD}{k} = 3.66$ for laminar flow in pipes

$$D_H = \frac{(4)(5)(10)}{30} = 6.667 \text{ mm} \qquad k = 0.6 \qquad \text{Nu}_T = 3.66$$

$$h = \frac{(3.66)(0.6)}{6.667 \times 10^{-3}} = 329.1$$

$$\frac{q}{L} = (329.1)(30 \times 10^{-3})(60 - 20) = 394.9 \text{ W/m}$$

6-6 Water at the rate of 3 kg/s is heated from 5 to 15◦C by passing it through a 5-cm-ID copper tube. The tube wall temperature is maintained at 90◦C. What is the length of the tube?

$$q = \dot{m}c_p(T_{b2} - T_{b1})$$

$$Re_d = \frac{\rho u_m d}{\mu}$$

$$u_m = \frac{\dot{m}}{\rho A} = \frac{\dot{m}}{\rho\left(\frac{\pi d^2}{4}\right)}$$

$$Re_d = \frac{\rho\left(\frac{\dot{m}}{\rho\left(\frac{\pi d^2}{4}\right)}\right)d}{\mu}$$

$$Re_d = \frac{4\dot{m}d}{\mu\pi d^2}$$

$$Re_d = \frac{4\dot{m}}{\mu\pi d}$$

$Nu_D = 0.023 Re_D^{0.8} Pr^n \qquad 0.6 < Pr < 100 \qquad 5.72$

N=0.4 for heating

$$q = (3)(4175)(15 - 5) = 125{,}850 \text{ W} \quad \text{at } 10°\text{C} \qquad \mu = 1.31 \times 10^{-3}$$

$$k = 0.585 \qquad \text{Pr} = 9.40 \qquad \text{Re} = \frac{(0.05)(3)(4)}{\pi(0.05)^2(1.31 \times 10^{-3})} = 58{,}316$$

$$\bar{h} = \frac{0.585}{0.05}(0.023)(58{,}316)^{0.8}(9.4)^{0.4} = 4283 \ \frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{C}}$$

$q = 125{,}850 = (4283)\pi(0.05)L(90 - 10)$ $\qquad L = 2.338\ \text{m}$

6-7 Water at the rate of 0.8 kg/s is heated from 35 to 40◦C in a 2.5-cm-diameter tube whose surface is at 90◦C. How long must the tube be to accomplish this heating?

$Nu_D = 0.023Re_D^{0.8}Pr^n \qquad 0.6 < Pr < 100 \qquad 5.72$

N=0.4 for heating

$q = \dot{m}c_p(T_{b2} - T_{b1})$

$q = (0.8)(4221)(40 - 35) = 16{,}884\ \text{W} \qquad \mu = 6.82 \times 10^{-4} \qquad \rho = 993$

$k = 0.63 \qquad \text{Pr} = 4.53 \qquad \text{Re} = \dfrac{(0.025)(0.8)(4)}{\pi(0.025)^2(6.82 \times 10^{-4})} = 59{,}741$

$$h = \frac{(0.023)(0.63)}{0.025}(59{,}741)^{0.8}(4.53)^{0.4} = 7024 \ \frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{C}}$$

$q = 16{,}884 = (7024)\pi(0.025)L(90 - 37.5)$ $\qquad L = 0.583\ \text{m}$

***6-8** Water flows through a 2.5-cm-ID pipe 1.5 m long at a rate of 1.0 kg/s. The pressure drop is 7 kPa through the 1.5-m length. The pipe wall temperature is maintained at a constant temperature of 50◦C by a condensing vapor, and the inlet water temperature is 20◦C. Estimate the exit water temperature.

$$u_m = \frac{\dot{m}}{\rho A} = \frac{\dot{m}}{\rho\left(\frac{\pi d^2}{4}\right)} = \frac{1}{998\left(\frac{\pi(0.025)^2}{4}\right)} = 2.04\ m/s$$

$$\Delta p = f\frac{L}{D}\rho\frac{u_m^2}{2}$$

$$7000 = f\frac{1.5}{0.025}(998)\frac{(2.04)^2}{2}$$

$f = 0.0562$

$T_f \approx \dfrac{50 + 20}{2} = 35^\circ\text{C} \qquad \text{at } 20^\circ\text{C} \qquad \rho = 998$

$c = 4180 \qquad \text{at } 35^\circ\text{C} \qquad \text{Pr} = 5.45$

$$St_b Pr_f^{\frac{2}{3}} = \frac{f}{8}$$

$$St_b = \frac{f Pr_f^{-\frac{2}{3}}}{8}$$

$$St_b = \frac{(0.0562)(5.45)^{\frac{-2}{3}}}{8} = 2.268 * 10^{-3}$$

$$St_b = \frac{Nu_D}{Re_D Pr}$$

$Nu_D = St_b * Re_D Pr$

$Re_d = \frac{u_m d}{v} = \frac{\rho u_m d}{\mu}$

$Pr = \frac{c_p \mu}{k}$

$Nu_D = St_b * \frac{\rho u_m d}{\mu} \frac{c_p \mu}{k}$

$Nu_D = \frac{hd}{k}$

$$h = \frac{Nu_D k}{d} = \frac{St_b * \frac{\rho u_m d}{\mu} \frac{c_p \mu}{k} k}{d} = St_b u_m \rho c_p$$

$$\bar{h} = (2.268 \times 10^{-3})(998)(4180)(2.04) = 19{,}297 \ \frac{\mathrm{W}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{C}}$$

$$q = h\pi DL \left(T_w - \frac{T_{b1} + T_{b2}}{2}\right) = \dot{m} c_p (T_{b2} - T_{b1})$$

$$q = (19297)(\pi)(0.025)(1.5)\left(50 - \frac{20 + T_{b2}}{2}\right) = (1)(4180)(T_{b2} - 20)$$

$T_{b2} = 32.83$°C

6-9 Water at the rate of 1.3 kg/s is to be heated from 60◦F to 100◦F in a 2.5-cm-diameter tube. The tube wall is maintained at a constant temperature of 40◦C. Calculate the length of tube required for the heating process.

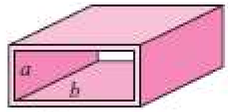
6-10 Water at the rate of 1 kg/s is forced through a tube with a 2.5-cm ID. The inlet water temperature is 15◦C, and the outlet water temperature is 50◦C. The tube wall temperature is 14◦C higher than the water temperature all along the length of the tube. What is the length of the tube?

6-11 Engine oil enters a 1.25-cm-diameter tube 3 m long at a temperature of 38◦C. The tube wall temperature is maintained at 65◦C, and the flow velocity is 30 cm/s. Estimate the total heat transfer to the oil and the exit temperature of the oil.

6-12 Air at 1 atm and 15◦C flows through a long rectangular duct 7.5 cm by 15 cm. A 1.8-m section of the duct is maintained at 120◦C, and the average air temperature at exit from this section is 65◦C. Calculate the airflow rate and the total heat transfer.

7.5×15 cm $\quad L = 1.8$ m $\quad$ air at 1 atm

$T_w = 120°C \quad T_b \text{ (inlet)} = 15°C \quad T_b \text{ (exit)} = 25°C$



$$D_h = \frac{4ab}{2(a+b)} = \frac{2ab}{a+b}$$

$$D_H = \frac{(4)(0.075)(0.15)}{(2)(0.075+0.15)} = 0.1 \text{ m} \qquad A_c = (0.075)(0.15) = 0.01125 \text{ m}^2$$

$$\overline{T_b} = \frac{T_{b1} + T_{b2}}{2}$$

$$\overline{T_b} = \frac{15+25}{2} = 20°C = 293 \text{ K}$$

Surface area= $A = 2(0.15 + 0.075)(1.8) = 0.81 \text{ m}^2$

$c_p = 1005 \quad \Pr = 0.7 \quad \mu = 1.83 \times 10^{-5} \quad k = 0.026$

$$q = \dot{m} c_p (T_{b_2} - T_{b_1}) = \bar{h} A (T_w - \overline{T_b})$$

$$\bar{h} = \frac{k}{D_H}(0.023)\left(\frac{\dot{m} D_H}{A_c \mu}\right)^{0.8} \Pr^{0.4} \qquad \text{Assuming turbulent}$$

$$\bar{h} = \frac{k}{D_H}(0.023)\left(\frac{\dot{m}D_H}{A_c\mu}\right)^{0.8} pr^{0.4}$$

$$q = hA\left(T_w - \frac{T_{b1}+T_{b2}}{2}\right) = \dot{m}c_p(T_{b2} - T_{b1})$$

$$\left(\frac{k}{D_H}(0.023)\left(\frac{\dot{m}D_H}{A_c\mu}\right)^{0.8} pr^{0.4}\right)(A)\left(T_w - \frac{T_{b1}+T_{b2}}{2}\right) = \dot{m}c_p(T_{b2} - T_{b1})$$

$$\left(\frac{0.026}{0.1}(0.023)\left(\frac{(\dot{m})0.1}{(0.01125)(1.83*10^{-5})}\right)^{0.8} 0.7^{0.4}\right)(0.81)\left(120 - \frac{15+25}{2}\right)$$
$$= \dot{m}(1005)(25-15)$$

$\dot{m} = 0.141$ kg/s

$q = (0.141)(1005)(25-15) = 1417$ W

$Re_{DH} = 68,500$ so turbulent assumption was correct.

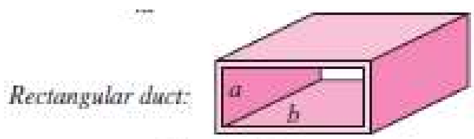
6-14 Water at an average temperature of 300 K flows at 0.7 kg/s in a 2.5-cm-diameter tube 6 m long. The pressure drop is measured as 2 kPa. A constant heat flux is imposed, and the average wall temperature is 55◦C. Estimate the exit temperature of the water.

6-15 An oil with Pr =1960, ρ=860 kg/m^3, ν=1.6×10^{-4} m^2/s, and k =0.14W/m· ◦C enters a 2.5-mm-diameter tube 60 cm long. The oil entrance temperature is 20◦C, the mean flow velocity is 30 cm/s, and the tube wall temperature is 120◦C. Calculate the heat-transfer rate.

6-18 Water at an average temperature of 10◦C flows in a 2.5-cm-diameter tube 6 m long at a rate of 0.4 kg/s. The pressure drop is measured as 3 kPa. A constant heat flux is imposed, and the average wall temperature is 50◦C. Estimate the exit temperatureof the water.

6-19 Water at the rate of 0.4 kg/s is to be cooled from 71 to 32◦C. Which would result in less pressure drop—to run the water through a 12.5-mm-diameter pipe at a constant temperature of 4◦C or through a constant-temperature 25-mm-diameter pipe at 20◦C?

6-24 An air-conditioning duct has a cross section of 45 cm by 90 cm. Air flows in the duct at a velocity of 7.5 m/s at conditions of 1 atm and 300 K. Calculate the heat-transfer coefficient for this system and the pressure drop per unit length.



$$D_h = \frac{4ab}{2(a+b)} = \frac{2ab}{a+b}$$

At 300 K and 1 atm. $\nu = 15.69 \times 10^{-6}$ $\rho = 1.1774$ $k = 0.02624$

$Pr = 0.708$ $D_H = \dfrac{(4)(45)(90)}{(2)(45+90)} = 60\text{ cm} = 0.6\text{ m}$

$$Re_{D_h} = \frac{u_m D_h}{v}$$

$$Re = \frac{(0.6)(7.5)}{15.69 \times 10^{-6}} = 2.87 \times 10^5$$

$$Nu_D = 0.023 Re_D^{0.8} Pr^n \quad 0.6 < Pr < 100$$

$n = 0.4$ heating

$$\bar{h} = 0.023 Re_D^{0.8} Pr^{0.4} * (\frac{k}{D_h})$$

$$\bar{h} = \frac{0.02624}{0.6}(0.023)(2.87 \times 10^5)^{0.8}(0.708)^{0.4}$$

$$\bar{h} = 20.35 \ \frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{C}}$$

$$\Delta p = f \frac{L}{d} \rho \frac{u_m{}^2}{2}$$

$$St_b Pr_f^{\frac{2}{3}} = \frac{f}{8}$$

$$\frac{Nu_D}{Re_D Pr} Pr_f^{\frac{2}{3}} = \frac{f}{8}$$

$$f = \frac{8 * \bar{h} * \frac{D_h}{k}}{Re_{D_h} Pr} Pr_f^{\frac{2}{3}}$$

$$f = \frac{8 * 20.35 * \frac{0.6}{0.02624}}{(2.87 * 10^5)(0.708)} (0.708)^{\frac{2}{3}}$$

$$f = 0.0145$$

$$\Delta p = f\frac{L}{d}\rho\frac{{u_m}^2}{2}$$

$$\Delta p = (0.0145)\left(\frac{1}{0.6}\right)\frac{(1.1774)(7.5)^2}{2} = 0.8 \text{ Pa}$$

*Flow cross cylinder and sphere

6-38 A 5-cm-diameter cylinder maintained at 100◦C is placed in a nitrogen flow stream at 2 atm pressure and 10◦C. The nitrogen flows across the cylinder with a velocity of 5 m/s. Calculate the heat lost by the cylinder per meter of length.

$$T_f = \frac{T_W + T_\infty}{2}$$

$$T_f = \frac{100+10}{2} = 55°\text{C} = 328 \text{ K} \qquad \mu = 19\times10^{-6} \qquad k = 0.0282$$

$$\text{Pr} = 0.7$$

$$\boldsymbol{\rho = \frac{p}{RT} = \frac{(2)(1.0132*10^5)}{(287)(328)} = 2.08 \text{ kg/m}^3}$$

$$Re_D = \frac{\rho u_\infty D}{\mu} = \frac{(2.08)(5)(0.05)}{19*10^{-6}} = 27377$$

From table 5.1

$$C = 0.193 \qquad n = 0.618$$

$$Nu_{Df} = \frac{hD}{k_f} = C\left(\frac{u_\infty D}{v_f}\right)^n Pr_f^{\frac{1}{3}}$$ (flow of gas)

$$h = \frac{k}{d}C\text{Re}^n\text{Pr}^{1/3} = \frac{0.0282}{0.05}(0.193)(27{,}377)^{0.618}(0.7)^{1/3} = 53.4$$

$$\frac{q}{L} = h\pi d(T_w - T_\infty) = (53.4)\pi(0.05)(100-10) = 755 \text{ W/m}$$

6-39 Air at 1 atm and 10◦C blows across a 4-cm-diameter cylinder maintained at a surface temperature of 54◦C. The air velocity is 25 m/s. Calculate the heat loss from the cylinder per unit length.

6-54 Calculate the heat-transfer rate per unit length for flow over a 0.025-mm-diameter cylinder maintained at 65◦C. Perform the calculation for (a) air at 20◦C and 1 atm and (b) water at 20◦C; u_∞ =6 m/s.

6-64 Air flows across a 4-cm-square cylinder at a velocity of 12 m/s. The surface temperature is maintained at 85◦C. Free-stream air conditions are 20◦C and 0.6 atm. Calculate the heat loss from the cylinder per meter of length.

6-65 Water flows over a 3-mm-diameter sphere at 5 m/s. The free-stream temperature is 38◦C, and the sphere is maintained at 93◦C. Calculate the heat-transfer rate.

6-67 A spherical tank having a diameter of 4.0 m is maintained at a surface temperature of 40◦C. Air at 1 atm and 20◦C blows across the tank at 6 m/s. Calculate the heat loss.

6-73 Air at 1 atm and 300 K flows across an in-line tube bank having 10 vertical and 10 horizontal rows. The tube diameter is 2 cm and the center-to-center spacing is 4 cm in both the normal and parallel directions. Calculate the convection heattransfer coefficient for this situation if the entering free-stream velocity is 10 m/s and properties may be evaluated at free-stream conditions.

6-75 Condensing steam at 150◦C is used on the inside of a bank of tubes to heat a cross flow stream of CO2 that enters at 3 atm, 35◦C, and 5 m/s. The tube bank consists
of 100 tubes of 1.25-cm OD in a square in-line array with *Sn* =*Sp* =1.875 cm. The tubes are 60 cm long. Assuming the outside-tube-wall temperature is constant at 150◦C, calculate the overall heat transfer to the CO2 and its exit temperature.

6-71 Air at 3.5 MPa and 38◦C flows across a tube bank consisting of 400 tubes of 1.25-cm OD arranged in a staggered manner 20 rows high; *Sp* =3.75 cm and *Sn* =2.5 cm. The incoming-flow velocity is 9 m/s, and the tube-wall temperatures are maintained constant at 200◦C by a condensing vapor on the inside of the tubes. The length of the tubes is 1.5 m. Estimate the exit air temperature as it leaves the tube bank.

At 38°C

$$\rho = \frac{p}{RT}$$

$$\rho = \frac{3.5\times10^6}{(287)(311)} = 39.2\ \text{kg/m}^3$$

$$T_f = \frac{T_W + T_{\infty,1}}{2}$$

$$T_f \approx \frac{200+38}{2} = 119°C = 392\ K$$

$$\rho_f = \frac{3.5\times 10^6}{(287)(392)} = 31.1\ kg/m^3$$

$\mu_f = 2.25\times 10^{-5}$ $\quad k_f = 0.0331$ $\quad Pr_f = 0.69$

$$c_p \approx 1010\ \frac{J}{kg\cdot °C}$$

$$\left\{\left[\left(\frac{S_n}{2}\right)^2 + S_p^2\right]^{\frac{1}{2}} - d\right\} * 2 = \left\{\left[\left(\frac{2.5}{2}\right)^2 + 3.75^2\right]^{\frac{1}{2}} - 1.25\right\} * 2 = 5.405$$

$$(S_n - d) = 2.5 - 1.25 = 1.25$$

Because

$$\left\{\left[\left(\frac{S_n}{2}\right)^2 + S_p^2\right]^{\frac{1}{2}} - d\right\} * 2 > (S_n - d)$$

Therefore:

$$u_{max} = u_\infty \left[\frac{s_n}{(s_n - d)}\right]$$

$$u_{max} = u_\infty\left(\frac{S_n}{S_n - d}\right) = 9\left(\frac{2.5}{2.5-1.25}\right) = 18\ m/sec$$

$$\frac{S_n}{d} = 2 \qquad \frac{S_p}{d} = 3$$

$$Re_{max} = \frac{\rho u_{max} d}{\mu_f}$$

$$Re_{max} = \frac{(31.1)(18)(0.0125)}{2.25\times 10^{-5}} = 311{,}000 \qquad C = 0.488 \qquad n = 0.562$$

$$Nu_{Df} = \frac{hD}{k_f} = C(Re_{max})^n Pr_f^{\frac{1}{3}}$$

$$h = \frac{d}{k_f} C(Re_{max})^n Pr_f^{\frac{1}{3}}$$

$$h = \frac{0.331}{0.0125}(0.488)(311{,}000)^{0.562}(0.69)^{1/3} = 1395$$

$$q = hA\left(T_w - \frac{T_{\infty,1} + T_{\infty,2}}{2}\right) = \dot{m}c_p(T_{\infty,2} - T_{\infty,1})$$

$$A = N\pi dL = 400 * \pi * 0.0125 * 1.5 = 23.56 \text{ m}$$

$$\dot{m} = \rho_\infty u_\infty S_n(20)L = 39.2 * 9 * 0.025 * 20 * 1.5 = 264.7 \text{ kg/s}$$

$$hA\left(T_w - \frac{T_{\infty,1} + T_{\infty,2}}{2}\right) = \dot{m}c_p(T_{\infty,2} - T_{\infty,1})$$

$$Q = (1395)(23.56)\left(200 - \frac{38 + T_{\infty,2}}{2}\right) = (264.7)(1010)(T_{\infty,2} - 38)$$

$T_e = 56.76°\text{C}$ $\quad\quad$ $q = 5.016 \text{ MW}$