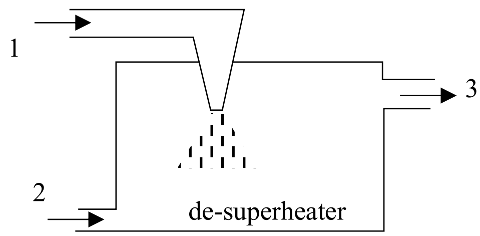
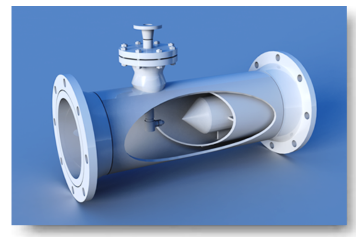
By injecting liquid water into superheated vapor, the de-superheater shown in the figure has a saturated vapor stream at its exit. Steady-state operating data are shown in the figure. Ignoring stray heat transfer and kinetic and potential energy effects, determine:

a. the mass flow rate of the superheated vapor stream, in kg/min, and
b. the rate of entropy production within the de-superheater, in kW/K.
c. Sketch the process on a *T*-*s* diagram.

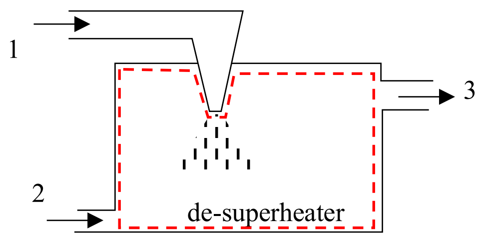


1: liquid water
20 °C, 0.3 MPa (abs)
6.37 kg/min
2: superheated vapor
200 °C, 0.3 MPa (abs)
3: saturated vapor
0.3 MPa (abs)



https://www.enggcyclopedia.com/2011/07/steam-desuperheater/

SOLUTION:



First apply Conservation of Mass to the control volume shown above,

$$\frac{dM}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}, \quad (1)$$

where,

$$\frac{dM}{dt} = 0 \quad \text{(steady state operation)}, \quad (2)$$

$$\sum_{in} \dot{m} - \sum_{out} \dot{m} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3, \quad (3)$$

Substituting,

$$\dot{m}_1 + \dot{m}_2 - \dot{m}_3 = 0. \quad (4)$$

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2. \quad (5)$$

Now apply the 1st Law to the same control volume,

$$\frac{dE}{dt} = \sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) + \dot{Q}_{in} - \dot{W}_{out}, \quad (6)$$

where,

$$\frac{dE}{dt} = 0 \quad \text{(steady state operation)}, \quad (7)$$

$$\sum_{in} \dot{m}(h + ke + pe) - \sum_{out} \dot{m}(h + ke + pe) = \dot{m}_1 h_1 + \dot{m}_2 h_2 - \dot{m}_3 h_3, \quad (8)$$

(neglecting changes in KE and PE between the inlets and outlets),

$$\dot{Q}_{in} = 0 \quad \text{(assuming the device is well insulated)}, \quad (9)$$

$$\dot{W}_{out} = 0 \quad \text{(the device is passive)}. \quad (10)$$

Substituting and solving for the mass flow rate at inlet 2, making use of Eq. (3),

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 - \dot{m}_3 h_3 = 0, \quad (11)$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2) h_3 = 0, \quad (12)$$

$$\dot{m}_1 (h_1 - h_3) + \dot{m}_2 (h_2 - h_3) = 0, \quad (13)$$

$$\dot{m}_2 = \dot{m}_1 \left(\frac{h_3 - h_1}{h_2 - h_3}\right). \quad (14)$$

Determine the properties at each inlet/outlet using the property tables for water.

State 1 (compressed liquid):

$T_1 = 20$ °C,

$p_1 = 0.3$ MPa (abs) = 3 bar (abs) > $p_{sat\,@\,20\,°C} = 0.023393$ bar (abs),

$v_{CL}(T_1, p_1) \approx v_f(T_1) = 0.0010018$ m^3/kg,

$h_{CL}(T_1, p_1) \approx h_f(T_1) + [p_1 - p_{sat}(T_1)]v_f(T_1) =$

= (83.914 kJ/kg) + (3 bar – 0.023393 bar)*(0.0010018 m^3/kg)*(100 kPa/bar) = 84.2122 kJ/kg,

$s_{CL}(T_1, p_1) \approx s_f(T_1) = 0.296480$ kJ/(kg.K).

State 2 (superheated vapor):

$T_2 = 200$ °C,

$p_2 = 0.3$ MPa (abs) = 3 bar (abs),

$h(T_2, p_2) = 2865.9$ kJ/kg,

$s(T_2, p_2) = 7.313$ kJ/(kg.K).

State 3 (saturated vapor):

p_1 = 0.3 MPa (abs) = 3 bar (abs),
$T_{sat\ @\ 3\ bar}$ = 133.52 °C,
$h(T_3, p_3)$ = 2724.9 kJ/kg,
$s(T_3, p_3)$ = 6.9916 kJ/(kg.K).

Substituting these values along with $\dot{m}_1$ = 6.37 kg/min (given) into Eq. (14),
$\boxed{\dot{m}_2 = 119 \text{ kg/min}}$ => (using Eq. (5)) $\dot{m}_3$ = 126 kg/min.

Now apply the Entropy Equation to the same control volume,

$$\frac{dS}{dt} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \int_b \frac{\dot{Q}_{in}}{T} + \dot{\sigma}, \quad (15)$$

where,

$$\frac{dS}{dt} = 0 \quad \text{(steady state operation)}, \quad (16)$$

$$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s = \dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3, \quad (17)$$

$$\int_b \frac{\dot{Q}_{in}}{T} = 0 \quad \text{(assuming the device is well insulated)}, \quad (18)$$

$$\dot{\sigma} = ? \quad (19)$$

Substitute and solve for the rate of entropy production,

$$\dot{\sigma} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2. \quad (20)$$

Using the previously evaluated parameters,
$\boxed{\dot{\sigma} = 0.0718 \text{ kW/K}}$. (Note that 1 kg/min = (1/60) kg/s.)
There is positive entropy production, as expected.