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Lab/Tutorial Report NO.	4

Report Title	Lab 4, Steam Quality Measurement

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Abstract:

This lab report presents the methodology and findings of steam quality measurements taken from the main building supply line of Kerr Hall East at Toronto Metropolitan University (TMU). Steam quality is quantified as the mass fraction of saturated vapour within the steam. The values recorded include the pressure and temperature of the inlet valves, alongside the weight of the steam. Also, the condensate temperature and pressure were recorded, and the enthalpy for both liquid and vapour phases was calculated. This report evaluates the steam quality, typically a combination of saturated vapour and a small amount of liquid water.

Introduction:

For finding the main requirement in this lab, which is the quality of steam given the variable being a fractional distillation of saturated water and vapour in said steam, is found by:

$$(x_1 = \frac{m_{Vapour}}{m_{liquid}+m_{Vapour}}) \tag{1}$$

Steam quality is a significant element in many daily life applications. For example, a mechanical engineer will need to find steam quality for a device called a steam turbine; something like this can be damaged if the steam quality falls too low, as liquid impingement on turbine blades can cause erosion.

The main issue corresponding with such an extremely low steam quality can easily be visible when looking at the performance and reducing heat transfer rates compared to higher ones as of the evident hindering heat exchanger. Therefore, it is essential to be able to evaluate the quality of steam in many industrial processes.

Since there are many methods of evaluating and discovering steam quality, the one used in the overall lab and further explained is separated into three smaller parts to make it easier. Firstly, the water collected in the bucket and jug is separated throughout the process and collected mechanically. This may be done using various methods, including vertically conveying the steam upwards via a large diameter pipe to limit its velocity, enabling huge water droplets to gather at the bottom.

A different strategy is to feed steam tangentially into a vertical pipe and let centrifugal forces cause water droplets to impact the pipe walls and drip down to the pipe bottom. Following the mechanical separation of bigger water droplets, the steam is throttled or driven via an aperture or valve that decreases the pressure of the steam while maintaining constant enthalpy. The throttled steam is then transported via a condenser, which condenses to saturated liquid and is collected. The process is illustrated in Figure 1 and on a p-v diagram in Figure 2. Note that it is necessary to include this stage as it ensures that the steam is nearly "dry" like state prior to the throttling in order that when the throttled steam emerges in a superheated condition.

The above method can be used for assessing the steam quality by running a steady-state system comprised of a mechanical separator and a condenser and collecting the condensate and mechanically separated liquid water over a known period of time while monitoring pressure and temperature at each stage of the process. A pressure and temperature measurement at point 3, right downstream of the throttle, allows the determination of h_3 from the steam table since, in the superheat region, p and T fix the state. Since throttling is a constant enthalpy process, $h_2 = h_3$ Once h, is known, x_2 can be determined from:

$$h_2 = (1 - x_2)h_f + x_2 h_g \qquad (2)$$

Assuming that all of the steam was condensed, the entirety of the mass of steam entering the system during the measurement interval equals the amount of condensate in addition to the total amount of mechanically separated liquid. As a result, the incoming steam's quality is provided by:

$$x_1 = \frac{x_2 m_{cond}}{m_{cond} + m_{sep}} \qquad (3)$$

Apparatus:

The following equipment was used to perform the experiment:

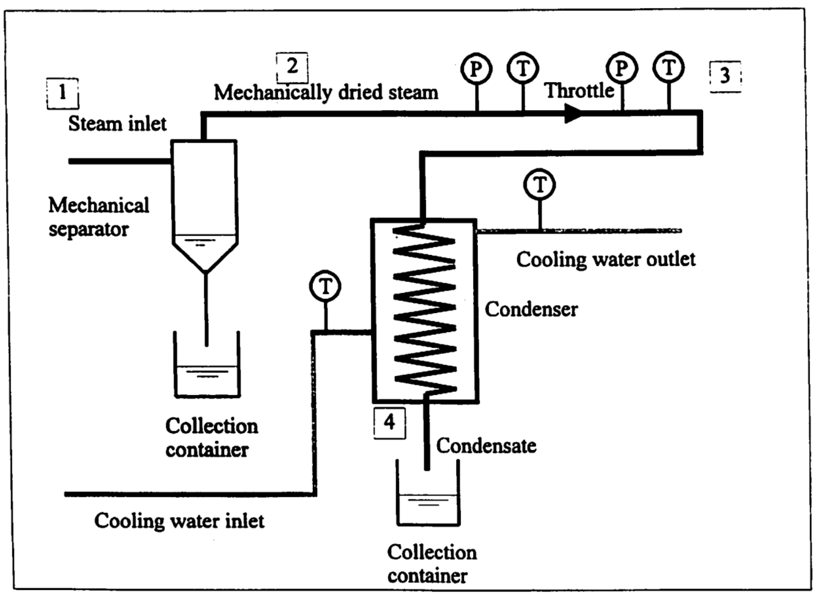

Figure 1: Steam quality measuring machine schematic diagram

Procedure:

1. Turn on the cooling water to the condenser
2. Open the steam stop valve, and slowly open the blow down valve to blow condensed water down the drain. continue blowing down until only steam emerges from the blow-down line then close the blowdown valve.
3. Open the separator steam inlet valve and allow the system to operate until steady state is reached (Condensate cooling water inlet and Outlet temperatures study).

4. Turn the three-way valve at the separator to the drain position to empty the separator of accumulated water, then shut the valve to begin accumulating liquid and start the clock.
5. Start collecting condensate from the condenser drain line and continue collecting for the time period specified by the instructor
6. Record all temperatures and pressures
7. At the end of The Collection period close to separators stream and valve and stop collecting condensate
8. To collect the mechanically separated water, crack the condenser steam inlet valve to slightly pressurise the system, and open the three way valve at the separator to direct the separated water to a beaker already containing a known mass of cold water to reduce burn hazard
9. Obtain at least three sets of readings and then Close the steam supply valve, wait five minutes, then close the condenser cooling water valves

Results:

Initial bucket weight: 2.255 kg
Initial Jug weight: 1.550 kg

Table 1: Results from Experiment

	Test Number:		
	1	2	3
Steam inlet Pressure (kPA)	350	349.5	350
Steam inlet Temp (℃)	141	142	143
Throttle Steam Temp (℃)	110	118	114
Throttle Steam Pressure (mmHg)	3.0	3.0	3.0
Cooling water outlet temp (℉)	74	85	54.5
Condensation Temp (℉)	52	52	73.8
Water Jug weight (kg)	1.580	1.655	1.730
Bucket weight (kg)	3.950	5.685	7.375

Table 2: Calculations Based on Experimental Results

	Test 1	Test 2	Test 3	Average
Linearly Interpolated hf (kJ/kg)	584.33	584.1037	584.33	584.2545667
Linearly Interpolated hg (kJ/kg)	2732.4	2732.329	2732.4	2732.376333
total pressure: (+patm) bar	1.021197358	1.021197358	1.021197358	1.021197358
h_g (lin inter):	2691.182753	2703.35	2697.259091	2697.263948
h_g of 3 (lin inter):	2676.267344	2676.267344	2676.267344	2676.267344
h_{g2} ($h_{g2} = h_{g3}$)	2676.267344	2676.267344	2676.267344	2676.267344
Steam Quality @ stage 1	**0.9569**	**0.9450**	**0.9408**	0.9476
Steam Quality @ stage 2	**0.9739**	**0.9739**	**0.9739**	0.9739

Sample Calculations:

Calculations for Trial 2:

Linear Interpolation for Saturated Liquid (hf) Using Table A3 From the Lab Manual:

Steam Inlet Pressure (Bar): 3.495

Table 3: Closest Table A3 Values to Steam Inlet Pressure

Pressure (bar)	Saturated Liquid (kJ/kg)	Saturated Vapour (kJ/kg)
3.5	584.33	2732.4
3	561.7	2725.3

$$\frac{p_{T2}-p_3}{p_{3.5}-p_3} = \frac{h_f-h_{f3}}{h_{f3.5}-h_{f3}}$$

$$h_f = (\frac{p_{T2}-p_3}{p_{3.5}-p_3}) \bullet h_{f3.5} - h_{f3}) + h_{f3}$$

$$h_f = (\frac{3.495-3}{3.5-3}) \bullet (584.33 - 561.7) + 2725.3$$

$$h_f = 584.33\ kJ/kg$$

Linear Interpolation for Saturated Vapour (hg) Using Table A3 from the Lab Manual:

$$\frac{p_{T2}-p_3}{p_{3.5}-p_3} = \frac{h_g-h_{g3}}{h_{g3.5}-h_{g3}}$$

$$h_g = (\frac{p_{T2}-p_3}{p_{3.5}-p_3}) \bullet h_{g3.5} - h_{g3}) + h_{g3}$$
$$h_g = (\frac{3.495-3}{3.5-3}) \bullet (2732.4 - 2725.3) + 2725.3$$
$$h_g = 2732.4\, kJ/kg$$

<u>Total Pressure in Throttle:</u>

$$p_{Total} = p_{atm} + p_{Measured}$$
$$= 1\, atm + 3\, mmHg$$
$$= 763.000138\, mmHg + 3\, mmHg$$
$$p_{Total} = 1.021197358\, mmHg$$

<u>Calculation of h at Throttle:</u>

Temperature at Throttle: 118℃
Pressure at Throttle: 1.021197358 bar

This temperature is non-existent on Table A3 from the lab manual. Use linear interpolation to find h.

Table 4: Closest Values on Table A3 to Throttle Temperature

Temperature (℃)	Saturated Liquid (kJ/kg)	Saturated Vapour (kJ/kg)
111.4	467.11	2693.3
120.2	504.7	2706.7

$$\frac{T_{T2} - T_{111.4}}{T_{120.2} - T_{111.4}} = \frac{h_g - h_{g111.4}}{h_{g120.2} - h_{g111.4}}$$
$$\frac{118-111.4}{120.2-111.4} = \frac{h - 2693.3}{2706.7-2693.3}$$
$$h_g = 2703.35\, kJ/kg$$

This pressure is non-existent on Table A3 from the lab manual. Use linear interpolation to find h.

Table 5: Closest Values on Table A3 to Throttle Pressure

Pressure (bar)	Saturated Liquid (kJ/kg)	Saturated Vapour (kJ/kg)
1	417.46	2675.5
1.5	467.11	2693.6

$$\frac{p_{T2}-p_1}{p_{1.5}-p_1} = \frac{h_{g3}-h_{g1.5}}{h_{g1.5}-h_{g1}}$$
$$h_{g3} = (\frac{p_{T2}-p_1}{p_{1.5}-p_1}) \bullet (h_{g1.5} - h_{g1}) + h_{g1.5}$$

$$h_{g3} = (\frac{1.022-1}{1.5-1}) \bullet (2693.6 - 2675.5) + 2675.5$$
$$h_{g3} = 2676.267344\ kJ/kg$$

As stated in the introduction throttling is a constant enthalpy process. Therefore, $h_{g2} = h_{g3}$:

$$h_{g2} = 2676.267344\ kJ/kg$$

Steam Quality at Stage 2:

Rearrange equation (2) to isolate for x_2:

$$h_2 = (1 - x_2)h_f + x_2 h_g$$
$$h_2 = h_{fg}$$
$$h_2 = h_f - x_2 h_f + x_2 h_g$$
$$h_2 - h_f = - x_2 h_f + x_2 h_g$$
$$x_2 = \frac{h_2 - h_f}{h_g - h}$$
$$= \frac{2703.35-584.33}{2732.4 - 584.33}$$
$$= 0.973903$$
$$x_2 = 0.9739$$

Steam Quality at Stage 1:

Use equation (3) to find steam quality at stage 1. As shown in the diagram, mass of condensation would be the weight of water collected in the bucket and mass of separator would be weight of water collected in the jug:

$$x_1 = \frac{x_2 m_{cond}}{m_{cond} + m_{sep}}$$
$$= \frac{(0.973903)(3.43)}{1.695 + 0.105}$$
$$= 0.9449754501$$
$$x_1 = 0.9450$$

Discussion:

Verify equation (3). What is the measured steam quality at points 1 and 2? Sketch the process on a Molier chart as found in Figure A-8 in Moran and Shapiro: Fundamentals of Engineering Thermodynamics 4th Ed. (John Wiley and Sons) or any other thermodynamics text. What are some expected sources of error in this experiment? What would be the effect of taking your measurements before steady state was reached (ie piping, valves etc. still cold)?

For reference equation (3) and (1):

$$(x_1 = \frac{x_2 m_{cond}}{m_{cond} + m_{sep}}) \qquad (3)$$

$$(x_1 = \frac{m_{Vapour}}{m_{liquid} + m_{Vapour}}) \qquad (1)$$

Seeing as the basis from equation 3 is derived from equation 1; there is a difference in steam where the steam from 1 has become something of its own, which later gets taken into account when tasked with finding the quality of the inlet steam. When looking at the figure and the calculations to further prove this point, it can be seen that from point 1 to point 2; there is essentially no change in pressure but only in volume. Because of this, it can be assumed that no vapour is present at the points as they hover between the transition line from liquid to vapour. Any possible errors seen in the lab can be caused mainly by human interference, and the device itself keeps leaking in different areas not meant to during the lab, which ultimately affected the collected data and all variations of this said data. These temperature variations would result in a different mass ratio of vapour to liquid, resulting in an inaccurate measure of steam quality.

Conclusions:

In conclusion, this experiment was an overall success as the objective of measuring and assessing the quality of steam drawn from the main building supply line of the steam quality testing device was met. The steam quality testing device collects and separates the produced liquid water from the saturated water vapour. Pressure and temperature measurements were taken over ten minutes, and using these measurements in conjunction with equations (1) and (2), steam qualities x_1 and x_2 were found. State one's steam quality x_1 was found to be 0.9450. State two's steam quality x_2 was found to be 0.9739. Any inaccuracies in data can be accredited to human error in reading the measurement dials. Possible experiment accuracy could have been achieved if digital dials were used for the most accurate measurement readings. Furthermore, accuracy could have been increased by measuring the temperature of the pipes as due to heat transfer, if a significant temperature difference were present, steam quality could be affected. Overall, this lab was a tremendous success.

References:

[1]Friedman, J., & Naylor, D. MEC511 *Thermodynamics & Fluid Mechanics Laboratory Manual.* Toronto, ON: Ryerson University.

[2]Moran, M. J., Shapiro, H. N., Boettner, D. D., & Bailey, M. B. (2019). *Fundamentals of engineering thermodynamics.* Milton, Qld: Wiley.

[3]D.F. Young, B.R. Munson, T.H. Okiishi; Wiley, 2007. *A Brief Introduction to Fluid Mechanics; 4th Edition.* John Wiley & Sons.

Appendices:

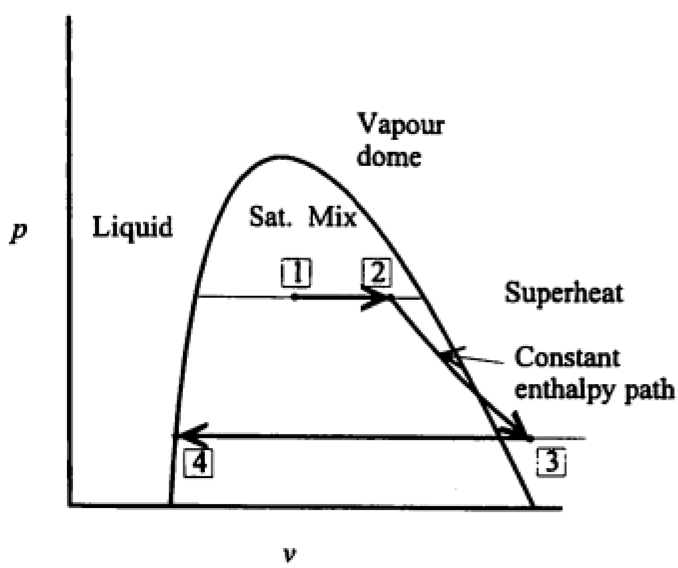

Figure 2: Process diagram

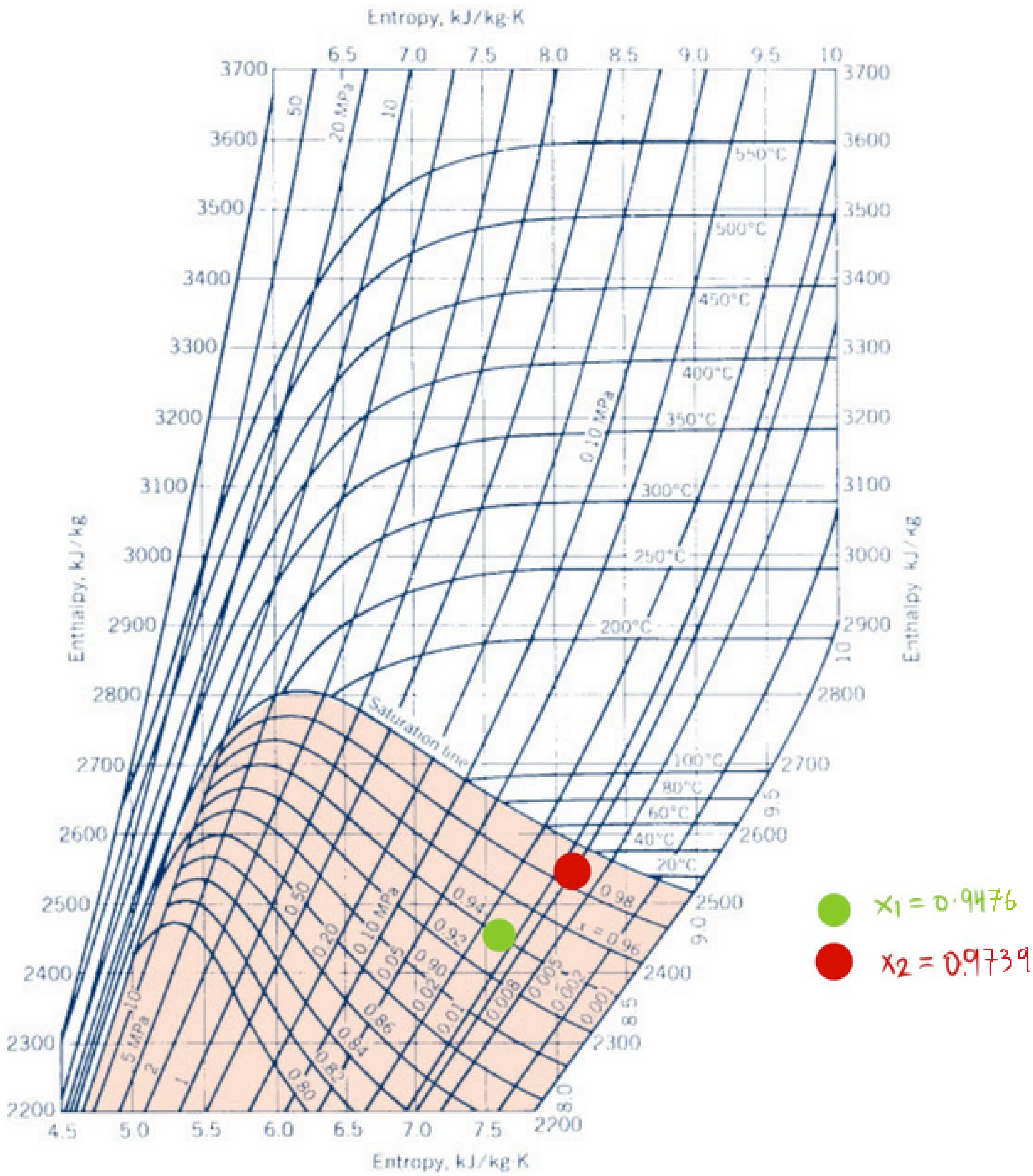

FIG. A.8 Enthalpy–entropy diagram for water (SI units). *Source*: J. B. Jones and G. A. Hawkins, *Engineering Thermodynamics*, 2nd ed., Wiley, New York, 1986.