Thermodynamics Labs
DT021 Year 4
Cooling Tower

David Collins
C10736685
david.collins4@mydit.ie

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1 Introduction

1.1 Objective

The goal of this experiment was to determine the effectiveness of a pilot-scale cooling tower (Figure 1), while also increasing our understanding of the basis of its operation.

1.2 Apparatus

We used the H892 benchtop cooling tower from P.A. Hilton Ltd. for this experiment. The setup includes 1. six thermometers / thermocouples for temperature measurements; 2. a manometer for air-flow recordings; and 3. a rotameter / flow-meter for measuring the water flow-rate. Lastly, there is a beaker to which 'make-up' water can be added to account for that lost in evaporation.

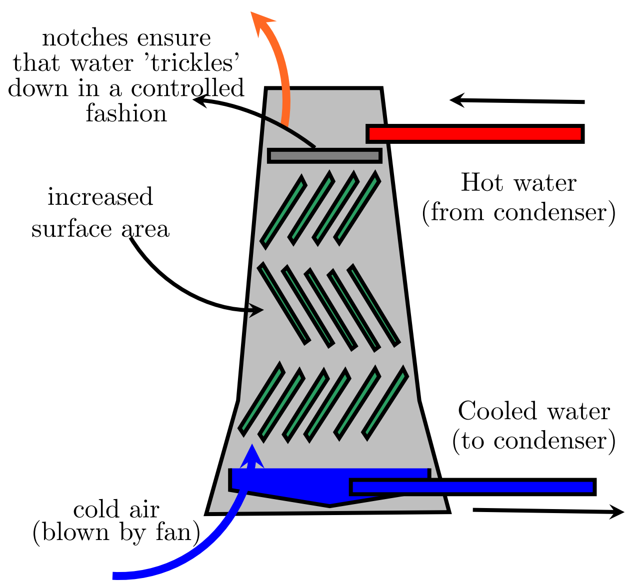

Figure 1: Induced-draft cooling tower

1.3 Why use cooling towers?

One may wonder why engineers go to the trouble of designing and building cooling towers in the first place? Why not just 'dump the heat in any old way'? Unfortunately, heat can not just be dumped indiscriminately in to the surroundings (e.g. rivers or lakes), as this can disrupt the ecosystem. More generally, cooling towers offer the advantage of increased control over how heat is transferred from a thermodynamic system to its surroundings.

1.4 Types of cooling towers

There are many variations of cooling towers — some of the most important differences being as follows.

- **induced draft vs. natural draft** Induced-draft towers use a fan or some other means to 'blow' the air over the water from the condenser. Natural-draft towers, in contrast, rely on the ambient air-flow to carry away the heat. Induced-draft towers have the advantage that they are eaiser to control, although they have higher running costs.
- **wet vs. dry** Some cooling towers mix the air with the water — these are known as 'wet' cooling towers. We use such a cooling tower in this experiment. Towers which prohibit the air from coming into direct contact with the water from the condenser are referred to as 'dry' towers.
- **counter-flow vs. cross-flow** This distinction is not of much interest to us in this experiment, but would probably be an important consideration in an industrial design.

2 Theory

We want a quantitative indication of how effectively the heat in the water is being transferred to the air. The rate at which the enthalpy of the air is changing, as given by Equation 1, is such an indicator.

$$\boxed{\text{Air enthalpy change (rate)} = \dot{m}_a(h_B - h_A)} \tag{1}$$

Before we can use Equation 1, however, we need to determine the mass flow-rate of the air, $\dot{m}_a$. This is given by Equation 2:

$$\boxed{\dot{m}_a = .0137\sqrt{\frac{x}{v_B}}} \tag{2}$$

where x is read from the manometer, and v_B is the specific volume as determined from the psychrometeric chart.

The rate of change of the enthalpy of the water is given by Equation 3:

$$\boxed{\text{Water enthalpy change (rate)} = \dot{m}_w C_p (T_5 - T_6)} \quad (3)$$

where $\dot{m}_w$ is the mass flow-rate of the water, C_p is the specific heat-capacity of water, and T_5 and T_6 are the inlet and outlet water temperatures respectively.

We also want to measure how quickly the water is evaporating (Equation 4):

$$\boxed{\text{Evaporation rate} = \dot{m}_a(\omega_B - \omega_A)}, \quad (4)$$

(where ω_B and ω_A denote kilograms of water per kilograms of dry air at the top and bottom of the tower respectively — as determined from the psychrometric charts), and how long it takes for the make-up water which is added to be 'used up' (Equation 5):

$$\boxed{\text{Make-up rate} = \frac{m}{t_{make_{up}}}}, \quad (5)$$

where m is simply the mass of the water added to 'make up' for that which has evaporated, and t_{make_up} is the length of time it takes for the volume of water in the system to return to its original level.

2.1 Psychrometry

Although it is not discussed in detail here, psychrometric charts were invaluable for this experiment. Many of the values in the above equations can only be determined by their use (or at least are determined more easily using psychrometric charts than by other means). These charts came into use in the early 1900s, and are ingenious way of relating various thermodynamic properties in moist air. Appendix A provides some examples.

3 Procedure

The steps in our experimental procedure are summarised below.

1. **Water temperatures** Using either a digital thermometer (thermocouples) or an analog thermometer, record the inlet and outlet water temperatures. This readings provide us with T_5 and T_6.
2. **Air temperatures** Record the wet-bulb temperature and dry-bulb temperature at both the top and bottom of the tower (four temperatures in total). These readings provide us with values T_1, T_2, T_3 and T_4.
3. **Air flow-rate** Using the manometer, record the air flow-rate in mm H20. This gives us the value x which will be used in Equation 2.
4. **Water flow** Record also the water mass flow-rate in g/s (indicated by the analog meter on the right-hand side of the unit). This gives $\dot{m}_w$.
5. **Derived quantities** Using the psychrometric charts (Appendix A) determine the derived quantities such as specific volume and the specific enthalpies. Then use Equations provided in Section 2 to determine the rates of change of enthalpy for both the water and air.

4 Measurements & Analysis

4.1 Readings / measurements

The measurements and recordings taken during the experiment are summarised in Table 1. Recall that temperatures T_1 — T_4 are those of air, while temperatures T_5 and T_6 are water temperatures (inlet and outlet respectively).

Initial observations Even before commencing our analysis, we can notice some general trends. The temperature of the water leaving the tower, for example, is less than that entering. This is what we expected and, of course, is the primary purpose of the tower to begin with. Notice, also, that the temperature difference (T_5 - T_6) increases in proportion to the power input, P.

Make-up water Due to shortcomings in the experimental set-up, the time indicated for the make-up water to evaporate, T, is significantly longer than expected in some cases. For the final case (with an heating element load of 1.5 kW), we accepted that there was a fault with the mechanism for adding make-up water. Consequently, the value indicated in this case is very approximate and should not be regarded as in any way reliable. The volume of make-up water added in all cases was 75 ml. Due to the density of water, this corresponds to a mass of 75 g.

P [kW]	T_1 [°C]	T_2 [°C]	T_3 [°C]	T_4 [°C]	T_5 [°C]	T_6 [°C]	x [mm H2O]	$\dot{m}_w$ [g/sec]	$t_{make_{up}}$ [s]
0.5	22.1	16.2	19.5	18.0	21.7	18.0	12.7	38.75	363
1.0	22.75	17.0	21.9	20.15	26.2	21.2	13.0	38.00	748
1.5	23.0	17.1	23.9	22.1	30.0	19.3	13.0	37.0	1200

Table 1: Measurements

4.2 Analysis

We need to determine the specific volume, moisture content, and specific enthalpy for each input power. We do this using the psychrometric charts, which are attached in Appendix A. Once we have these, we can proceed with the analysis.

The detailed analysis for the case of input power, $P = 1.5$kW, is presented below. That for the other two cases is precisely the same.

	v [$\mathrm{m^3\,kg^{-1}}$]	ω [$\mathrm{kg\,kg^{-1}}$]	h [$\mathrm{kJ\,kg^{-1}}$]
A (Bottom)	.848	.0092	45.7
B (Top)	.845	.0124	51.0

Table 2: **P = 0.5**kW — Derived quantities for case 1

	v [$\mathrm{m^3\,kg^{-1}}$]	ω [$\mathrm{kg\,kg^{-1}}$]	h [$\mathrm{kJ\,kg^{-1}}$]
A (Bottom)	.853	.00975	48.0
B (Top)	.856	.0142	58.0

Table 3: **P = 1.0**kW — Derived quantities for case 2

	v [$\mathrm{m^3\,kg^{-1}}$]	ω [$\mathrm{kg\,kg^{-1}}$]	h [$\mathrm{kJ\,kg^{-1}}$]
A (Bottom)	.8525	.00975	48.2
B (Top)	.863	.016	64.8

Table 4: **P = 1.5**kW — Derived quantities for case 3

Using Equation 2, we can find the **mass flow-rate of the air**.

$$\dot{m}_a = .0137\sqrt{\frac{13.0}{.863}} = 53.17\mathrm{g\,s^{-1}}$$
$$= .0532\mathrm{kg\,s^{-1}}.$$

Using Equation 1, we next find the **rate-of-change of enthalpy for the air**.

$$\text{Air enthalpy change (rate)} = \dot{m}_a(h_B - h_A)$$
$$= (53.17 \cdot 10^{-3}\mathrm{kg\,s^{-1}})((64.8 - 48.2)\mathrm{kJ\,kg^{-1}})$$
$$= .882\mathrm{kJ\,s^{-1}} = .882\mathrm{kW}$$

Let us compare this with the **rate-of-change of enthalpy for the water** (Equation 3).

$$\text{Water enthalpy change (rate)} = \dot{m}_w C_p(T_5 - T_6)$$
$$= (37.0 \cdot 10^{-3}\mathrm{kg\,s^{-1}})(4.18 \cdot 10^3\mathrm{J\,K^{-1}\,kg})((30 - 19.3)\mathrm{K})$$
$$= 1655\mathrm{J\,s^{-1}} = 1.655\mathrm{kW}$$

The evaporation rate, as given by Equation 4, is

$$\text{Evaporation rate} = \dot{m}_a(\omega_B - \omega_A) = (.0532\mathrm{kg\,s^{-1}})(.0160 - .00975)$$
$$= .3 \cdot 10^{-3}\mathrm{kg\,s^{-1}}.$$

Lets compare this to the make-up rate (Equation 5).

$$\text{Make-up rate} = \frac{m}{T} = \frac{75 \cdot 10^{-3}\mathrm{kg}}{1200\mathrm{s}} = .0625 \cdot 10^{-3}\mathrm{kg\,s^{-1}}$$

5 Results

The detailed analysis for one of the cases was provided in the preceding section. Following the same procedure for the other two cases, we arrive at the results summarised in Table 5. P_a and P_w denote the rate of change of enthalpy for air and water respectively. These have the same units (kW or $\mathrm{kJ\,s^{-1}}$) as the electrical power used by the heating element.

The results are portrayed graphically in Figure 2.

5.1 What we expected

6 Conclusion

6.1 What we learned

Lessons we learned include the following.

- **Basics of cooling towers** We learned that — although seemingly simple — cooling towers demand care in their design, and that there is a large body of science behind their operation. Perhaps most importantly, we learned why they are needed in the first place (Section 1).

	P [kW]	P_a [kW]	P_w [kW]	$\dot{m}_{evap}$ [kg s^{-1}]	$\dot{m}_{make_up}$ [kg s^{-1}]
1	0.50	0.28	.60	$.163 \cdot 10^{-3}$	$.21 \cdot 10^{-3}$
2	1.00	0.53	.79	$.236 \cdot 10^{-3}$	$.10 \cdot 10^{-3}$
3	1.50	0.88	1.66	$.30 \cdot 10^{-3}$	$.0625 \cdot 10^{-3}$

Table 5: Summary of results

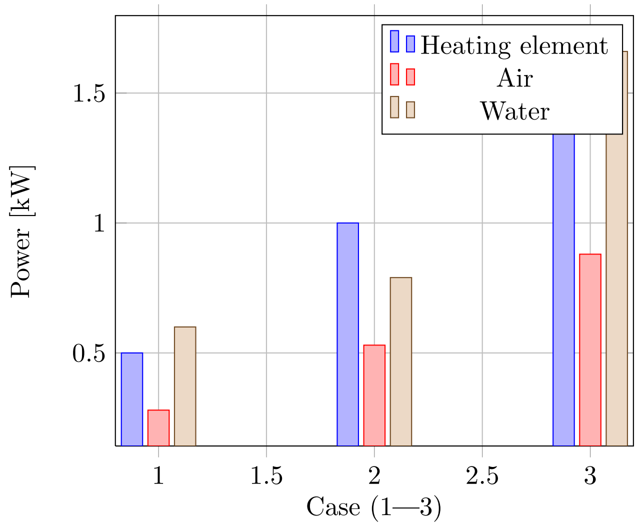

Figure 2: Comparison

- **Thermodynamics** We reminded ourselves that — using basic thermodynamics and simple physical concepts (such as specific heat capacity, mass flow-rate, etc.) — we can draw consequences and derive properties about a complex system such as moist air.
- **Psychrometric charts** We learned how to read a psychrometric chart properly, which in turn provided us with a deeper understanding of the properties of moist air (and how these properties relate to each other).

6.2 Experimental error

The results were not as expected. Although there was some correlation between the power supplied to the heating element and the rate at which heat was dissipated to the water and air, there were significant discrepancies between the values in each case. We can note at least two possible reasons for this.

- **Temperature readings** The digital thermometers used may not have been calibrated before the experiment, and thus their results can not necessariliy be regarded as reliable.
- **Heating element** If there was any sort of limescale deposits on the heating elements, this may have severely limited the transfer of heat from the elements to the water.

A Psychrometric charts

Notice that the change in enthalpy, $\Delta h = h_B - h_a$, increases in proportion to the amount of the heat transferred to the water by the heating element. Despite the experimental anomalies, the presence of this general trend is at least encouraging.

The charts for each case are presented in Figures 3 – 5.[1]

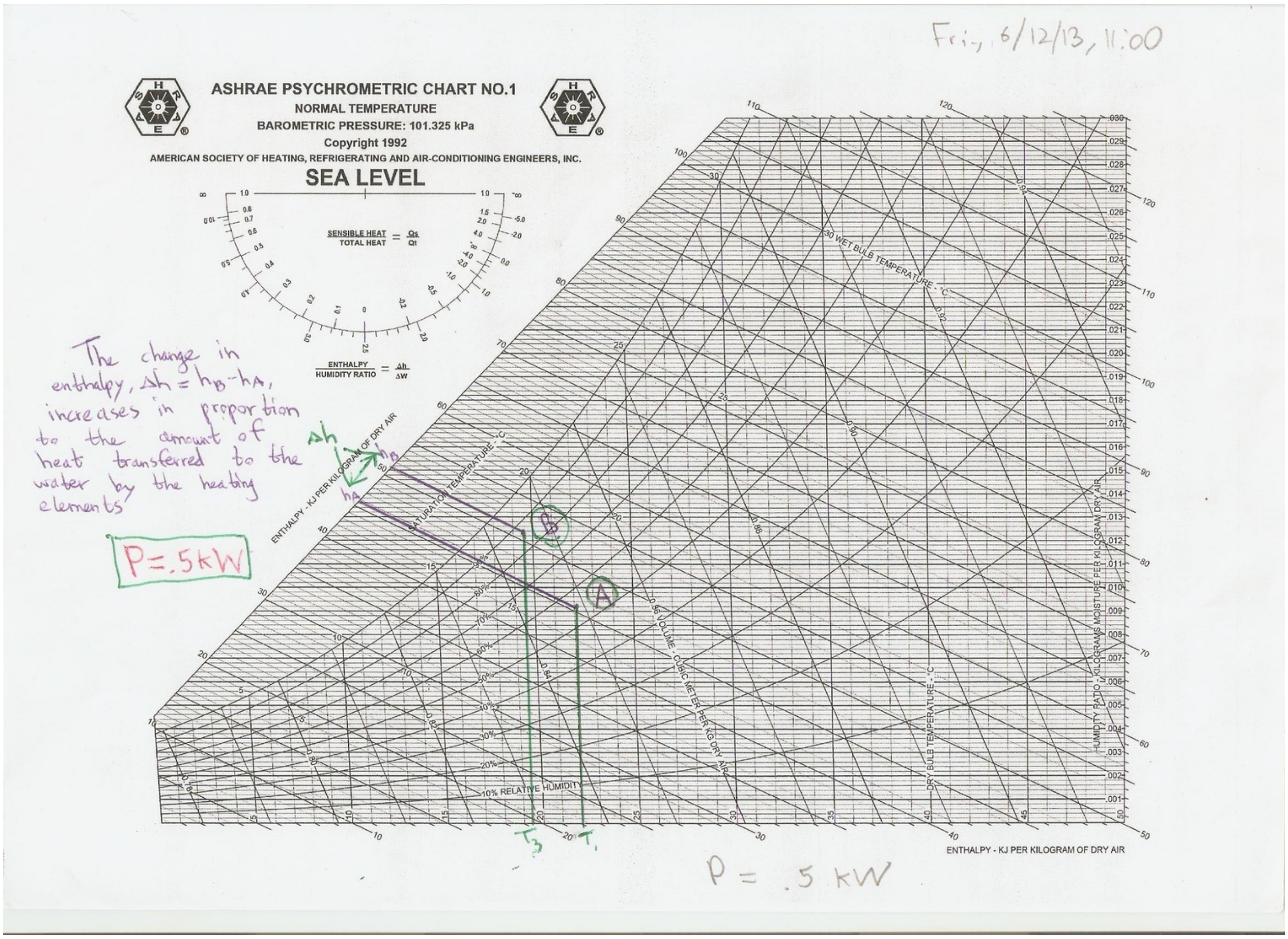

Figure 3: Psychrometric chart, case 1 (Power = .5 kW)

[1] Click the icon in the captions to download PDFs of the charts.

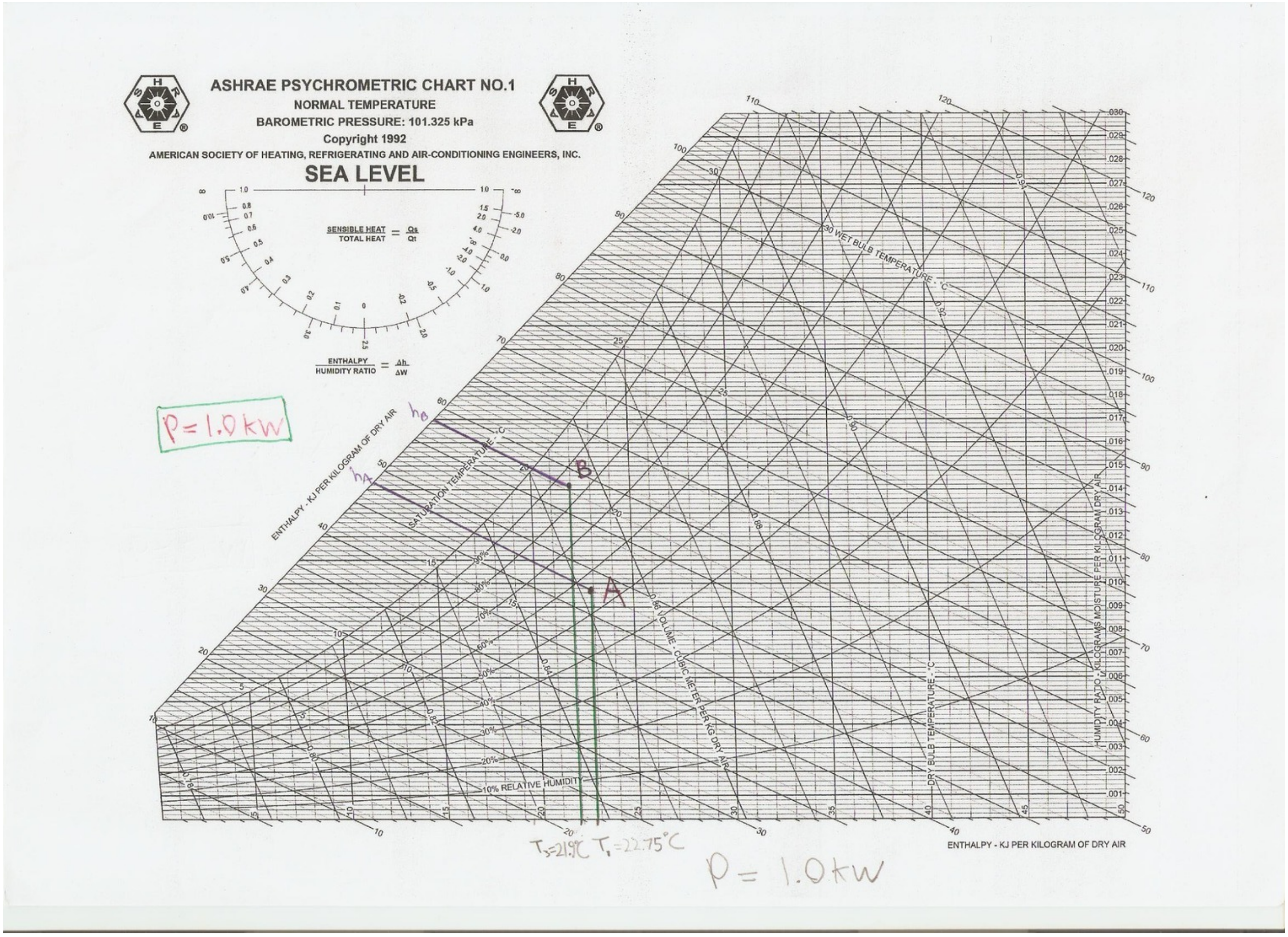

Figure 4: Psychrometric chart, case 2 (Power = 1.0 kW)

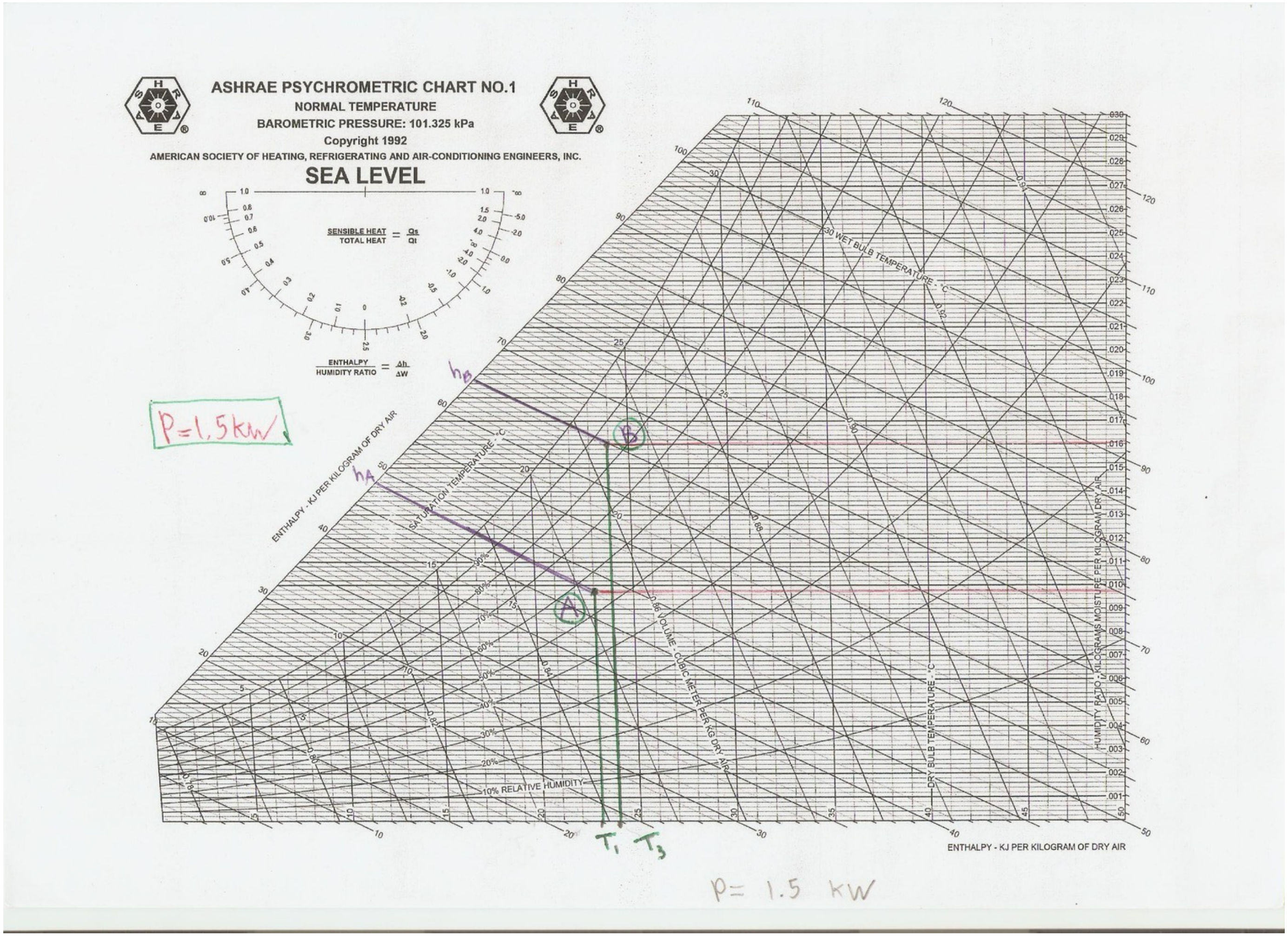

Figure 5: Psychrometric chart, case 3 (Power = 1.5 kW)