Experiment 2: Analysis of the Combined Rankine and Vapour Compression Cycle

Introduction

The Rankine cycle is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work while undergoing phase change. Vapor compression cycle is one of the many refrigeration cycles and is the most widely used method as heat-pump or as a refrigerator. The vapor-compression uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. External mechanical work should be put into to circulate this cycle. For this combined Rankine and vapour compression cycle, the external mechanical work input required to drive a vapour compression cycle can be provided by a Rankine cycle.

Objectives

- To investigate the combined Rankine and vapour compression cycle
- To carry out thermal advantage analysis of a vapour compression cycle as a heat pump/refrigerator

Theory and Principles

The work input required to drive a vapour compression cycle can be provided by a Rankine cycle as shown in the accompanying plant and *p-h* diagrams.

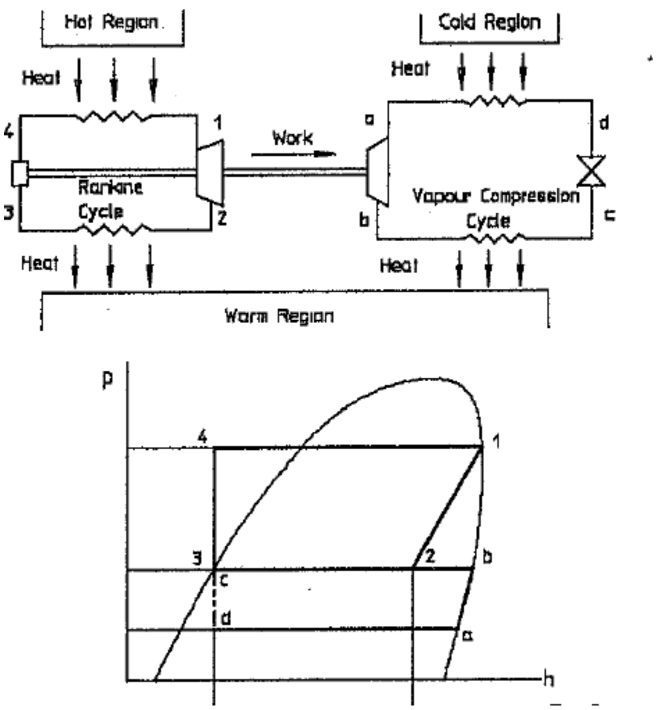


Figure 1. Diagram of combined Rankine and vapour compression cycle

Note: The *p-h* diagram shown assumes that the same fluid flows in both cycles, but it should be appreciated that the mass flow rates will be different.

Since processes b - c and 2 - 3 above take place at the same temperature and end as saturated liquid, they can take place in the same condenser as shown below.

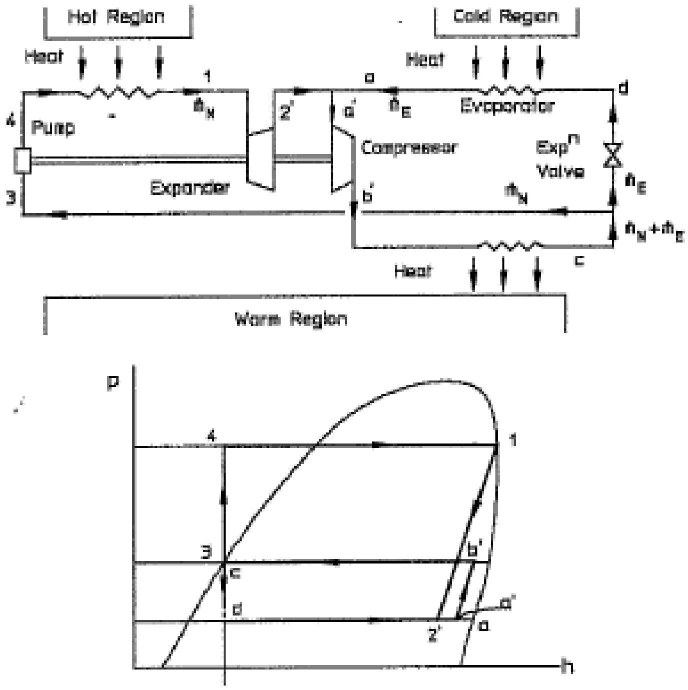


Figure 2. Diagram of combined Rankine and vapour compression cycle when the processes b – c and 2 - 3 are taken place in the same condenser

Note: a' is the result of mixing together fluid at condition (2') and fluid at condition (a).

Let the mass flow rates in the Rankine cycle be $\dot{m}_N$ and in the vapour compression cycle be $\dot{m}_E$.

Neglecting all losses, the power developed by the turbine is equal to the power absorbed by the compressor, or

$$\dot{m}_N(h_1 - h_{2'}) = (\dot{m}_N + \dot{m}_E)(h_{b'} - h_{a'}) \qquad (1)$$

For the mixing process, $\dot{m}_N h_{2'} + \dot{m}_E h_a = (\dot{m}_N + \dot{m}_E)h_a$ (2)

The Heat supplied from the hot region $= \dot{m}_N(h_1 - h_4)$ (3)

The Heat taken in from the cold region $= \dot{m}_E(h_a - h_d)$ (4)

The Heat delivered to the warm region $(\dot{m}_N + \dot{m}_E)(h_b - h_c)$ (5)

The thermal advantage of the device as a heat pump

$$= \frac{Heat\ delivered\ to\ warm\ region}{Heat\ supplied\ from\ hot\ region} = \frac{(\dot{m}_N + \dot{m}_E)(h_b - h_c)}{\dot{m}_N(h_1 - h_4)} \qquad (6)$$

And as a refrigerator

$$= \frac{Heat\ extracted\ to\ cold\ region}{Heat\ supplied\ from\ hot\ region} = \frac{\dot{m}_E(h_a - h_d)}{\dot{m}_N(h_1 - h_4)} \qquad (7)$$

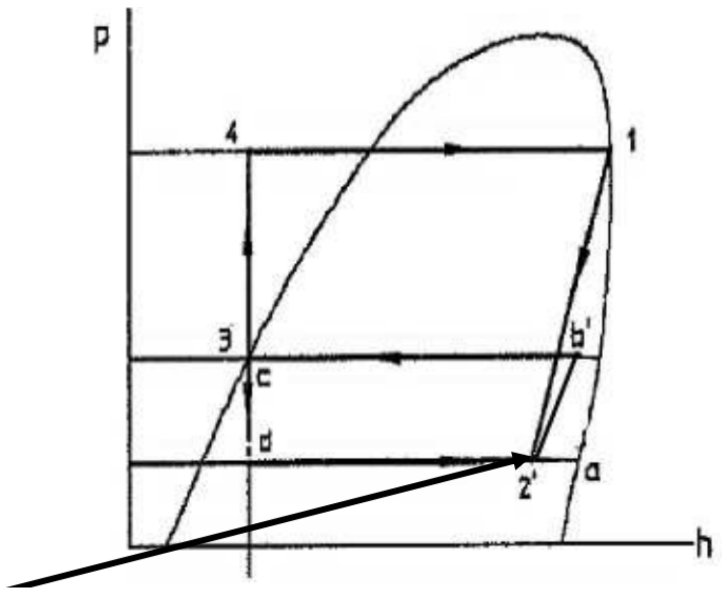


Figure 3. Assume that state points 2' and a' coincide to simplify calculation

In order to simplify calculations in this text, it is convenient and of sufficient accuracy to assume that state points 2' and a' coincide, i.e. it is assumed that the vapour leaving the evaporator has the same quality as the vapour leaving the nozzle.

Equipment and Useful data

- Hilton R853Vapour Jet Refrigerator/Heat Pump
- Useful data : *p-h* diagram of SES36 (please refer to Appendix)

Procedure

1) Check if the system under normal operation, and give the evaporator heater variable transformer a low heat input, e.g. 50W.
2) The throttle valve should be fully open and the condenser cooling water adjusted to the maximum measurable flow rate.
3) Allow the unit to stabilize, usually 5 minutes are enough to achieve steady state condition. And then begin to observe the following phenomenon.
   Observe: the places where the energy transfers occur, including:
   a. At the generator - heat is transferred to the refrigerant liquid from hot water. This produces refrigerant vapour at a pressure dependent upon the water temperature t_1.
   b. At the evaporator - heat is transferred at a low temperature to the refrigerant and from the surroundings. This is the "refrigerating effect".
   c. At the condenser - heat is transferred from the refrigerant to the cooling water. This would be the useful effect as a “heat pump”.
   d. At the feed pump - work (i.e. the product of force and movement) is transferred from the pump piston to the refrigerant liquid. (This work input is very small - only about 5W).
4) Adjust the variable transformer for evaporator heater slowly to a medium-high value. Allow the unit to stabilize.
5) Reduce the evaporator heater voltage by a small amount, and reduce the condenser water flow rate to bring the condenser temperature back to its original value. When the unit is stabilization, record the data on Table 1.
6) Plot all state points on a *p-h* diagram, evaluate all the enthalpies.
7) Calculate the thermal advantage as a heat pump / refrigerator and filled the results in Table 2.

Diagram Key:

1 Main Switch,
2 Pump Switch
3 Evaporator Heater Switch
4 Generator Switch
5 Evaporator Heater Control
6 Tank Thermostat
7 Evaporator Ammeter
8 Evaporator Voltmeter
9 Vapour Generator Pressure
10 Nozzle Inlet Pressure
11 Temperature Indicator
12 Evaporator Pressure
13 Condenser Pressure
14 Ejector
15 Condenser
16 Condenser water Flow Control
17 Evaporator
18 Expansion Valve Float
19 Throttle Valve
20 Solenoid Valve
21 Water Flowmeter
22 Vapour Generator Chamber
23 Refrigerant Sight Glass
24 Water Sight Glass
25 Tank Filling Valve
26 Vapour Generator Relief Valve
27 Condenser Relief Valve
28 Feed pump

Figure 4. Photo of Hilton R853 Vapour Jet Refrigerator/Heat

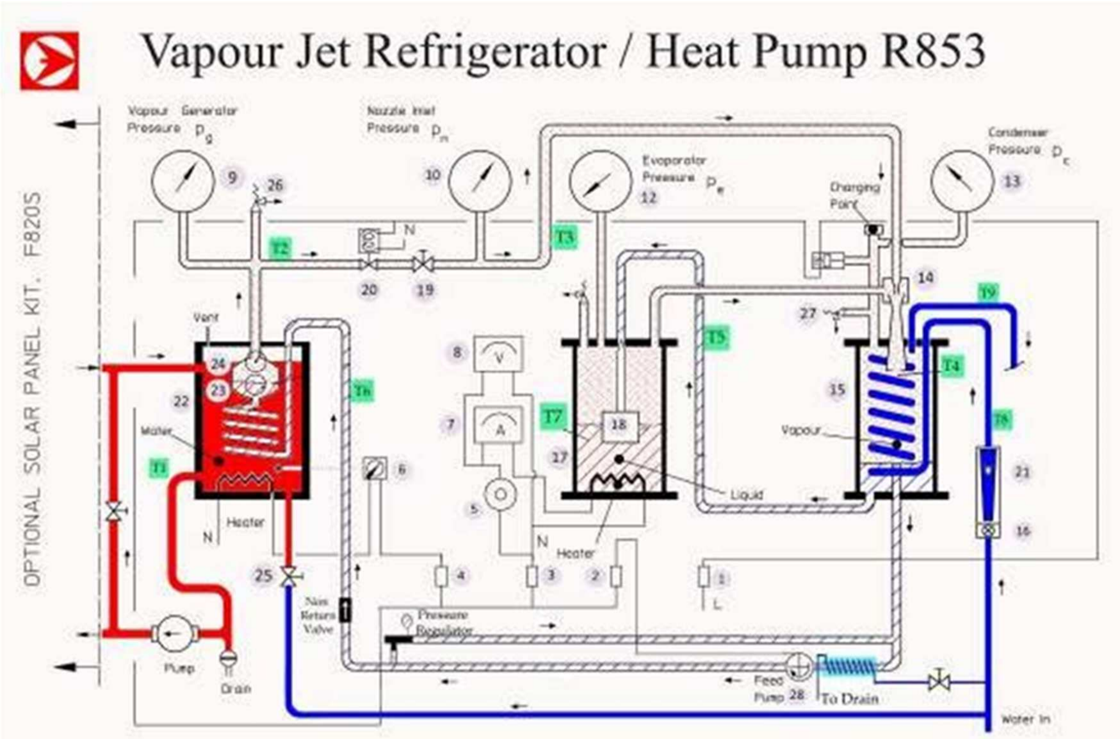


Figure 5. Diagram of Hilton R853 Vapour Jet Refrigerator/Heat

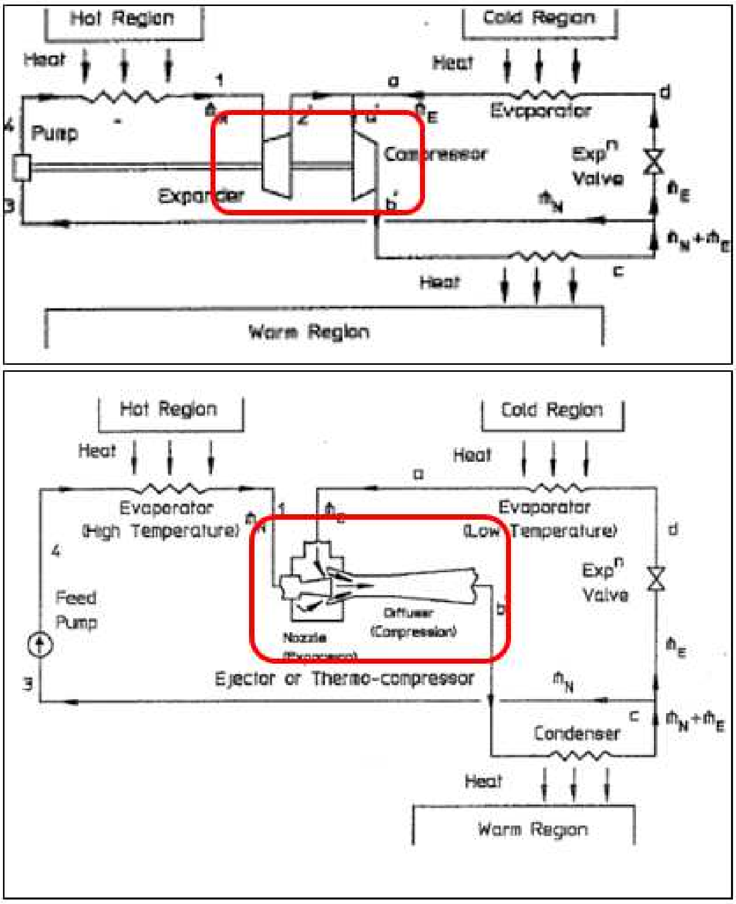


Figure 6. In the Hilton Vapour Jet Refrigerator/Heat Pump the expansion process 1 - 2 takes place in the nozzle of the ejector and the compression process a' - b' takes place in the diffuser instead of the compressor. The theoretical analysis of the two idealized cycles is the same.

Results

The Table 1 provided in the Appendix are for recording the measurement data and calculation procedure. After the experiment, the following information should be established to report the findings.

- Clear presentation of the measurement data.
- Plot all points on a *p-h* diagram (SES36) to represent the combined Rankine and vapour compression cycle.
- Calculations of the thermal advantage as a heat pump / thermal advantage as a refrigerator.
- Figures illustrate the comparison of the thermal advantage varies from evaporating temperature and condensing temperature when the unit acting as a heat pump and a refrigerator.

Discussions

The following issues shall be evaluated and discussed.

- Understanding the combined Rankine and vapour compression cycle.
- Understanding the definition of the thermal advantage of a heat pump and a refrigerator.
- Factors affecting the thermal advantage of a heat pump and a refrigerator.

Laboratory Report

Each student should prepare their own report based on the data and information obtained during the experiment. While the results from the observations and measurements can be shared among the members in the same student group, each student shall generate information to show his/her own understanding and ideas. Students making direct copy of the information in others' report (plagiarism), if found, will be disqualified.

The laboratory report in PDF format shall be submitted to the Moodle before the deadline. Late submission will receive reduction in marks.

References

ASHRAE, 2017. *ASHRAE Handbook Fundamentals 2017*, SI edition, Chp. 2: Thermodynamics and Refrigeration Cycles, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed., Chp. 9, McGraw-Hill, New York.

Web Links

Vapour Compression Refrigeration Cycle Calculator http://engr.usask.ca/classes/ME/227/Refrigeration/js/

/PY/17/10/

Appendix

Table 1. Observed Data

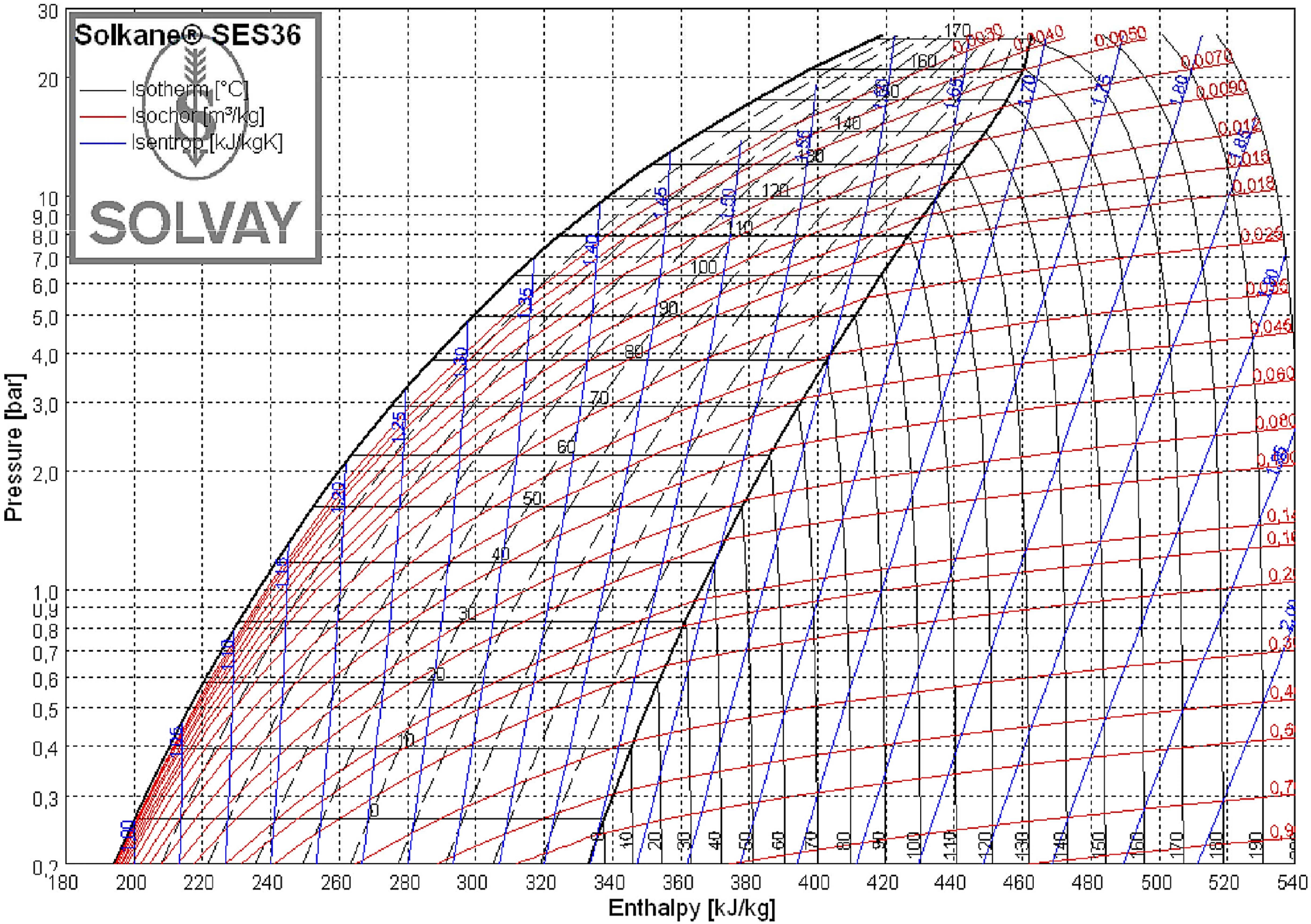
Ambient Temperature (t_a): ______________°C
Atmospheric Pressure (P_a): ______________kN m^{-2}

TEST No.			1	2	3
Vapour Generator	Water Temperature	t_1 °C			
	Vapour pressure	p_g kN m^{-2} gauge			
	Vapour temperature	t_2 °C			
Nozzle Inlet (Ejector)	Vapour pressure	p_n kN m^{-2} gauge			
	Vapour temperature	t_3 °C			
Evaporator	Vapour pressure	p_e kN m^{-2} gauge			
	Temperature	t_7 °C			
	Potential Difference	Volts			
	Current	Amp			
Diffuser (Ejector)	Vapour temperature	t_4 °C			
Condenser	Vapour pressure	p_g kN m^{-2} gauge			
	Saturation temperature (from SES36 Chart or Tables)	°C			
	Water mass flow rate	m_w g s^{-1}			
	Water inlet temperature	t_8 °C			
	Water outlet temperature	t_9 °C			
Liquid Refrigerant return	Refrigerant to evaporator	t_5 °C			
	Refrigerant to generator	t_6 °C			

Table 2. Summary of Calculated Thermal Advantage as a Heat Pump / a Refrigerator

Condensing pressure (kMm^{-2}, gauge) ________________
Condensing Temperature (°C) ______________

No.	Evaporator heater input current (Amp)	Evaporating Temperature (°C)	Thermal Advantage as a:	
			Heat pump	Refrigerator
1				
2				
3				


Solkane® SES36
Isotherm [°C]
Isochor [m³/kg]
Isentrop [kJ/kgK]
SOLVAY
Pressure [bar]
Enthalpy [kJ/kg]