CONTROL OF A SOLAR HEAT PUMP

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ABSTRACT

Refrigerant flow instability in heat pumps has been acknowledged for many years. This hunting problem in solar-boosted heat pumps may be attributed to inappropriate thermostatic expansion valve use, long evaporator tubes, and rapidly changing solar conditions. Control devices such as electronic expansion valves can be used to tackle the problem satisfactory. However, the price of the electronic expansion valve prohibits the use of it especially for a small heat pump such as household water heating system where heating capacity does not exceed 10 kW. Therefore, in general, a simple thermostatic expansion valve is used extensively in such systems. Experimental work from this study showed that hunting can be minimized by using a slightly under-sized capacity orifice in the TEV. However, higher degree of superheating is the side effect of this modification. It was also found that allowing some degree of hunting (DOH) by using an oversize orifice in the system may save up to 5% of energy input.

1 INTRODUCTION

A solar-boosted heat pump is primarily designed to upgrade low temperature heat sources into high temperature output. The evaporator is especially designed to collect energy from two main heat sources: solar energy and ambient air. A long finned evaporator is generally used to maximise heat input from these heat sources. For a typical 5 kW heating capacity heat pump, evaporator tube length can be up to 25 meters. Another fact of the solar-boosted heat pump is that it relies so much on natural heat sources, which can be unexpectedly varied from time to time. On a good sunny day, if cloud is present this can reduce the evaporating temperature of a heat pump from 23° C to 7° C. Good control devices should react to these factors in a reasonable time and deliver the right mass flow to the evaporator.

In practice, a proportionally controlled thermostatic expansion valve (TEV) is widely used to determine and supply working fluid in solar-boosted heat pumps. The TEV senses a superheating signal from the evaporator outlet and then use this signal to meter the amount of working fluid. It is expected that at specific range of working conditions, the TEV should be able provide a uniform refrigerant mass flow at an expected rate. However, due to long evaporator path and dramatic change in evaporating temperature, mass flow instability or so-called hunting is almost inevitable. A general form of hunting is the oscillated movement of the TEV's orifice or needle, which results in cyclic fluctuations of refrigerant mass flow rate. Other causes of hunting are summarised in ASHRAE (1994). Several investigators have reported hunting phenomena in many different applications such as in Huelle (1972), Gruhel and Isermann (1985), Ibrahim (1998), Mithraratne et al (2000) and Ibrahim (2001). However, there is very little mention of hunting in solar-boosted heat pumps.

Therefore, this paper will investigate and report on the flow instability in a solar-boosted heat pump water heater. Some basic considerations and modifications to this heat pump are also discussed in order to minimize this hunting problem.

2 EXPERIMENTAL RIG

The heat pump water heater used in the experiment is a commercial model available in Australia and some other countries. The maximum rated energy transfer to water is 5.3 kW at 20° C ambient temperature. The refrigeration circuit of the heat pump consists of a condenser coil, a refrigerant receiver, a TEV, three 1.9 m^2 evaporator plates, and a 1.1-kW rotary compressor. This heat pump uses R-22 as its working fluid. The 250-L water storage tank is wrapped around by the carbon steel condenser coil where superheated working fluid vapour enters at the top and condensed working fluid leaves at the bottom. The compressor, TEV, and refrigerant receiver are placed on top of the storage tank. The evaporator plates are separated and connected to the other components via long copper tubes. The tank wall is thermally insulated to minimise heat losses. The TEV used is the TX2 series from Danfoss (part number 068Z3281). This TEV has no maximum operating pressure limitation and has internal pressure equalisation. The evaporator plates are aluminium-finned tube and are black-painted on one side. The plates are vertically installed and face the black side to receive solar radiation.

Solar radiation supplied to the evaporators is artificially created by using ten 1.5 kW electric heaters. These heaters are installed in such a way so that radiation on the evaporators is evenly distributed. The magnitude of solar radiation is electronically adjusted by a controller. Detailed of the artificial solar radiation and the controller can be found in (Dixon 1979). Realistically, solar radiation availability is different for each geographical location and time of year. Maximum solar radiation at the space outside the earth atmosphere is about 1377 W/m^2. It is absorbed and reflected by the earth's atmosphere and particles in the air before it reaches the earth ground. For example, monthly average daily solar radiation in Melbourne, Australia is about 700 W/m^2. Assuming that the fin efficiency of the evaporators used is 0.8, the maximum cooling capacity of the evaporators is, therefore, 3.2 kW.

There are two TEVs installed parallel to each other on the test rig. The first TEV was equipped with no.02 orifice. This orifice has cooling capacity of 3.5 kW, rated at T_e = 5° C, T_c = 32° C, DSH = 11 K, and DSC = 5 K. Static superheat is 4 K and Opening superheat is 6 K. The orifice installed in the second TEV has rated cooling capacity of 2.5 kW (so called no.01). As can be seen clearly, the no.02 orifice is slightly oversized while the no.01 is matched. Installation of the TEV and orifices complied with technical information provided on the Danfoss website (Danfoss 2001). Gate valves are installed in front of each TEV for diverting refrigerant flow direction to a desired TEV.

Calibrated measurement devices; including thermocouples, pressure transducers, refrigerant flow meter, water flow meter, and power meter, were installed to collect real time data during experiment. Data retrieved during the experiments from this equipment were recorded by a data logger. Schematic diagram of the heat pump and location of measurement devices is shown in.

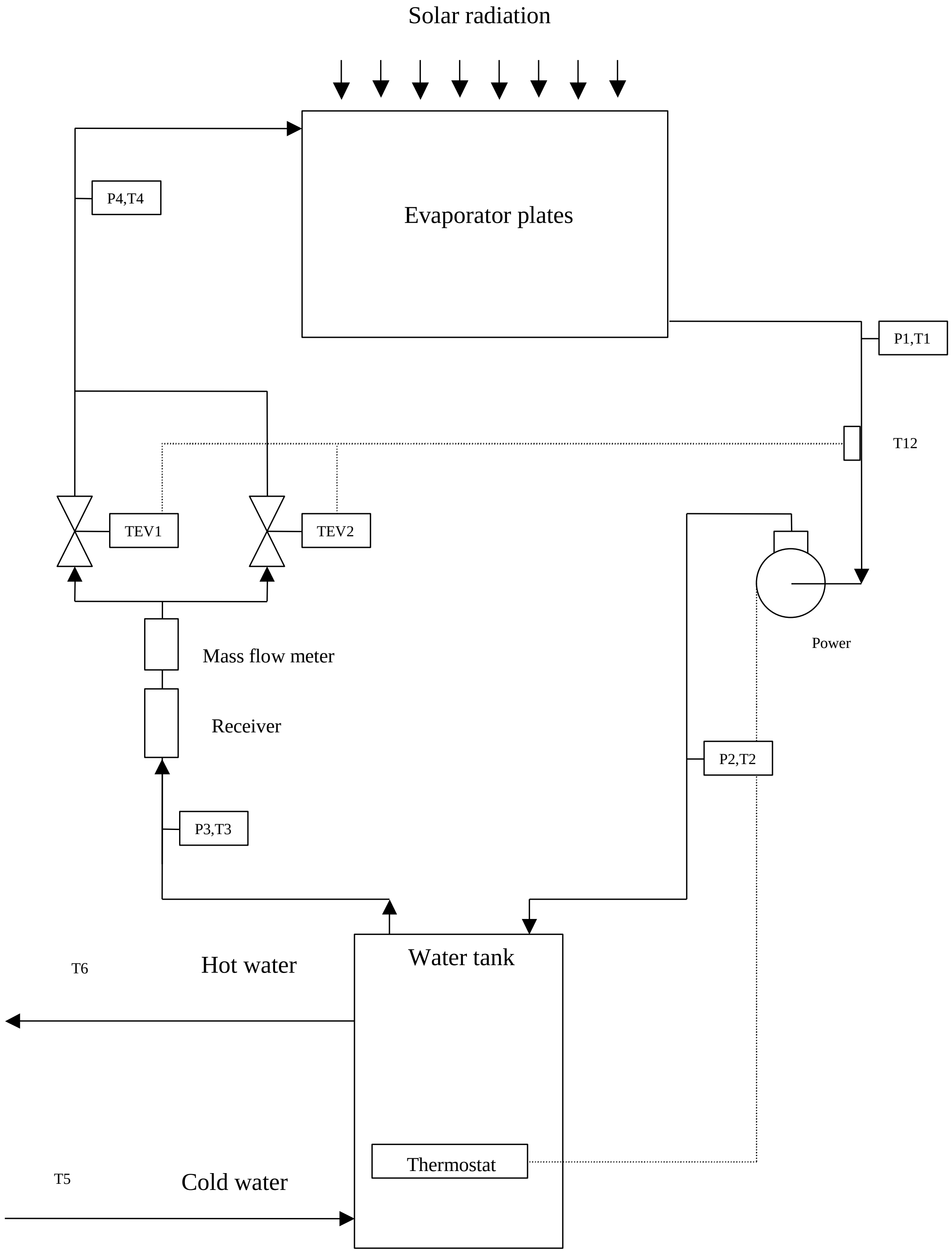

Figure 1 Schematic diagram of the heat pump water heater

3 EXPERIMENTAL RESULTS

3.1 Solar radiation test

This experiment is for investigating the basic responses of both orifices under various magnitudes of solar radiation; 0, 600, and 1100 W/m^2. Initially, the evaporator plates are heated by the electric heaters for about half an hour at a desired solar radiation level before starting the experiment. Average initial water temperature in the tank was at about 20° C and final temperature at about 60° C. Before commencing each test, the tank has to be filled with cold water (about 20° C). Also, the systems were left over night until every component reached its rest stage to minimise embedded energy in the systems. Then the heat pump is switched on as well as the data-logging device.

Flow stabilities of R-22 were experimentally observed. Generally, in the first half hour from starting up, flow of the refrigerant was not stable, as the energy balances between refrigerant and heat source/sink were not reached. After this period, if the TEV can sense the right signal from the evaporator outlet and consequently feed right amount of mass flow rate to the evaporators the oscillation should be eliminated. Results showed that the orifice no.01 could adjust the flow to a uniform rate until the end of tests at solar radiation of 600, and 1100 W/m^2. Orifice no.02 also shared the same behaviour at 1100 W/m^2 radiation. Both orifices, however, introduced hunting at zero radiation. Example of mass flow patterns can be seen clearly in Figure 2 and Figure 3. Please note that the unit for time in X-axis represents time lapsed during the experiment.

In these tests, the fluctuations of the mass flow rate were found to repeat. These repeating patterns looked like a sine wave with a constant period of about 4 minutes. However, the amplitudes of these wave patterns decreased as the time increased.

It was also interesting that at the end of every test the mass flow fluctuation always disappears or minimizes. In each test, heat input to the evaporator plates was constant throughout the heating period, which results in a certain refrigerant mass flow rate. The TEV employs a proportional control algorithm. DSH at the evaporator outlet is used as feedback signal to the TEV to determine the amount of mass flow rate. For the orifice no.02, a unit change in DSH results in greater refrigerant mass flow or bigger damping. Therefore, it takes longer time to reach convergence. Sometimes, the convergence cannot be achieved at all.

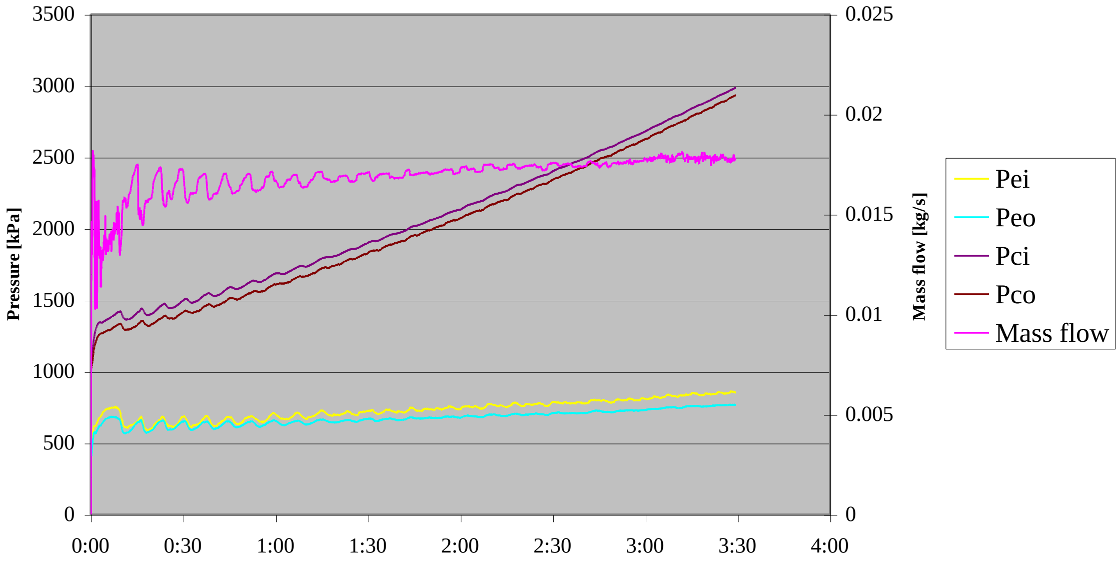

Figure 2 Pressure and refrigerant mass flow rate - orifice no.01 - 600 W/m^2

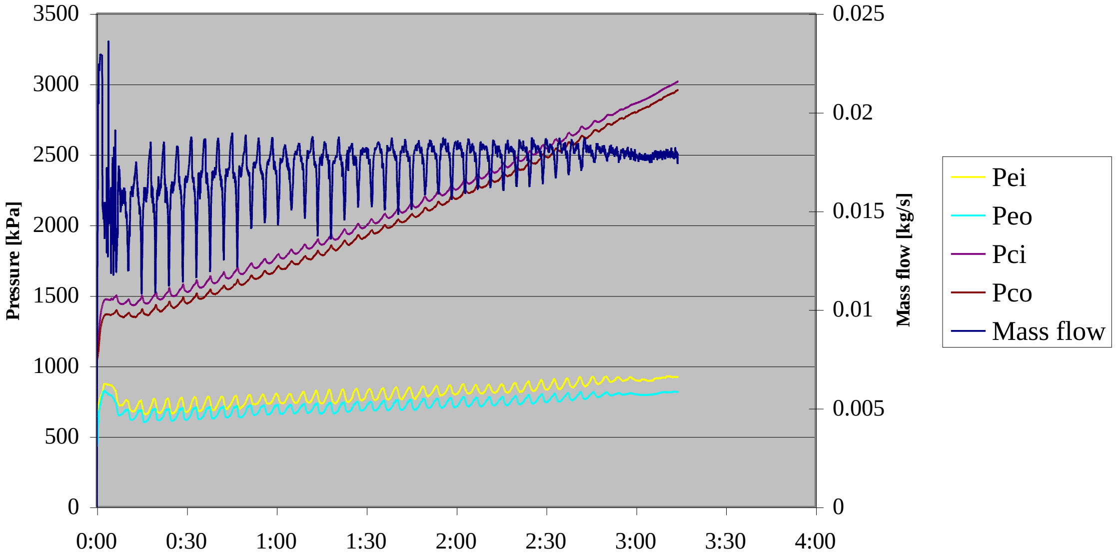

Figure 3 Pressure and refrigerant mass flow rate – orifice no.02 - 600 W/m^2

The above figures also show pressure profiles of both orifices at 600 W/m^2 heat input. It is clear that in cases where hunting is present fluctuations of evaporating pressure and condensing pressure are to be expected due to changes of mass flow rate. As a result, associated temperatures are also variable. As mentioned earlier, hunting in the orifice no.02 is greater hence the pressure fluctuation is also greater.

At higher solar radiation, mass flow rate increases as the TEV tried to maintain a proper DSH. In the case of orifice no.02, the mass flow rate could be increased while DSH remains in the range of 11 K. For example, at 1100 W/m^2 solar radiation, the maximum mass flow rate was

0.023 kg/s and DSH was 7 K. However, the orifice no.01 could not deliver this much refrigerant mass flow as this exceeds its maximum capacity. The maximum mass flow rate of orifice no.01 was only 0.018 kg/s. Evidently, it resulted in increased DSH at the evaporator outlet. The maximum DSH found at 1100 W/m^2 was 26 K. This DSH was clearly greater than the rated DSH, which is 11 K.

Each of the orifices used in the experiments has its own cut-off solar radiation, where above this radiation level, the hunting is no longer present. These cut-offs were at approximately 400 W/m^2 and 800 W/m^2 for the orifice no.01 and no.02 respectively.

3.2 Responding to rapid reduction in solar radiation

This experiment aims to investigate the responses of each orifice to the rapid changes of solar radiation supplied to the evaporator. Most of the time in actual operation of solar-boosted heat pumps, energy from solar radiation can be suddenly reduced by cloud cover in the sky. This unexpected reduction can cause overfeeding to the evaporators. Solar radiation was originally, in this test, set at 1100 W/m^2 then reduced to 0 W/m^2. The condensing pressure was maintained constant for both orifices.

From the experiments, it was found that orifice no.01 could cope with that great drop in solar radiation much better than orifice no.02. After the radiation on the plates was reduced, orifice no.01 responded to the change by gradually decreasing the mass flow rate to a proper rate with a few small damping oscillations until the mass flow rate was stable. DSH before the radiation reduction was high. After rapid reduction, it dropped sharply to below 0 K for about 3 minutes before it returned to a proper level. Once DSH became stable the mass flow rate was also stable. The mass flow remained at this stable rate until the end of the heating period.

However, In the case of orifice no.02, the refrigerant mass flow rate dropped sharply and remained fluctuating. DSH also dropped to below 0 K. After that the DSH fluctuated almost until the end of the heating period.

4 DISCUSSION

4.1 Degree of Hunting (DOH)

ASHRAE (1994) stated that "*Extreme hunting reduces the capacity of the refrigeration system because the mean evaporator pressure and temperature are lowered and the compressor is reduced*". However, no quantitative figure has been given on what magnitude of hunting is considered extreme. By definition, hunting is cyclic overfeeding and starving of refrigerant feed to evaporator. Therefore, in this study, hunting caused by a TEV will be represented by Degree of Hunting (DOH), which can be expressed by the following equation:

$$DOH = \frac{MaxMassFlow - MinMassFlow}{MaxMassFlow} \times 100\%$$

The refrigerant mass flow rates used in the above equation are liquid mass flow rates that are measured before entering the TEV. If a heat pump has no hunting problem DOH is 0%. On the other hand, if hunting is serious DOH increases. Please note that, highest DOH is 100%. The DOH can also be used to represent the fluctuation of heat output at the condenser because the heat output is the product of mass flow rate multiplied by the refrigerant enthalpy change at the condenser. This adds a more meaningful sense to this new term. The following table shows DOHs obtained from the experiments. In this table, the two figures in each cell represent DOHs at the beginning and the end of each test.

Table 1 Degree of Hunting (%) at different solar radiation

Orifice	Radiation (W/m^2)		
	0	***600***	***1100***
No.01	10/0	8/0	0/0
No.02	40/10	38/0	10/0

Table 1 shows that only the orifice no.01 could maintain the stability of refrigerant mass flow rate at the whole range of the radiation. During the tests, it was observed that the orifice no.01 struggled to stabilise the mass flow rate in a short period. Especially at 1100 W/m2 radiation, there was no sign of instability due to not enough refrigerant mass flow supplied as discussed in section 3.1.

Values of DOH below 10% indicate small oscillation in evaporating pressure and condensing pressure. Use of compressor in cases where pressures are fluctuating can reduce service life of the compressor. The fluctuation can cause constant vibration in the compressor parts and increase rate of worn out in long-term usage. Ultimately, volumetric efficiency of the compressor decreases. However, this argument has not been quantitatively verified in this study.

From this study, it was found that the average evaporator pressure and temperature of the solar-boosted heat pump increases at high DOH, which is contradictory to the statement in ASHRAE (1994). The increased evaporator pressure and temperature are the result of greater refrigerant mass flow across the evaporator. This will be discussed in more detail in the following section.

4.2 Effects on the system performance during actual operation

From the previous section, DOHs of the orifice no.02 were quite large at 0 and 600 W/m^2 radiations. This instability incurs the pressure fluctuations at evaporator and condenser. These fluctuations affect performance of the solar-boosted heat pump. The pressure and mass flow fluctuations at condenser leads to oscillated heat delivery at the condenser. Therefore, cycle COP becomes oscillated, as illustrated in Fig 4. Note that, the COPs were calculated from enthalpies of the refrigerant and measured power consumption during the experiments. The sampling frequency is 2 seconds. In general, the COP decreases due to increased condensing pressure at the end of the heating period, which widens the temperature lift between the evaporator and condenser.

The amplitudes of the COPs from both orifices are different. Large variation in amplitude found in orifice no.02 is the result of higher changes in heat delivery at the condenser. These changes are caused by two main factors; refrigerant mass flow rate and consequent heat transfer coefficient on the refrigerant side. If the mass flow rate is high the heat transfer coefficient of the refrigerant is also high. Thus, the heat rejected, which depends on these two factors, increases.

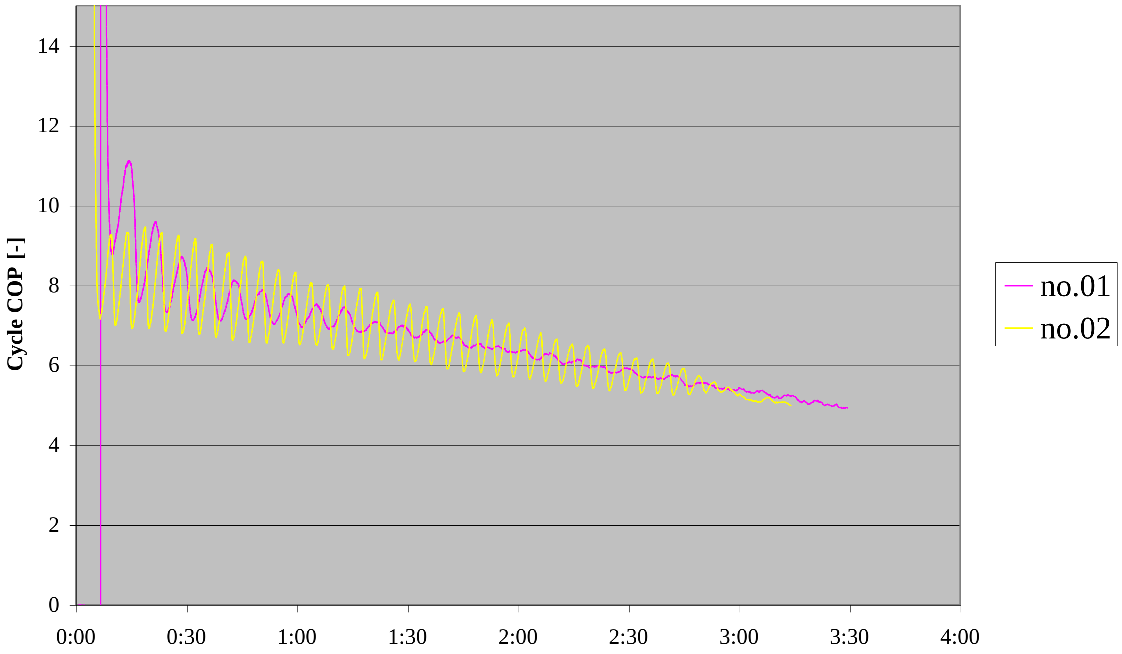

Figure 4 Comparison of instant COP for both orifices at 600 W/m^2 radiation

On average, the evaporating pressure of the orifice no.02 is slightly higher than that of the orifice no.01 due to higher mass flow rate. According to Figure 2 and Figure 3, the average mass flow rate of the orifice no.02 is about 2% higher than that of the orifice no.01. This has two direct effects on the system performance. Firstly, the increased evaporating pressure minimises the gap between the condensing pressure and evaporating pressure. Secondly, the larger mass flow rate reduces the DSH at the evaporator outlet, which improves compression process efficiency. Hence, for both reasons, the work required in the case of orifice no.02 is less. From three different radiation tests, average power consumption of the system with the orifice no.02 is about 5 % less than that of the orifice no.01. Accordingly, the time used in water heating is also less.

Although the average power consumption of orifice no.02 is less there is a great risk of liquid refrigerant entering the compressor. From the test at zero radiation, DSH of this system was oscillating in the range of 0 to 7 K. Remember that the factory-set static superheat of this TEV is 5 K. this indicates that most of the time the TEV was closed because DSH is lower than static superheat. In addition, if the solar radiation decreases rapidly the risk becomes higher since there is time lag in the evaporator.

4.3 *Simple solutions?*

It is difficult dealing with hunting in this solar-boosted heat pump. The time lag and solar energy fluctuation are the major inevitable causes of this problem. Moreover, the characteristics of the TEV also limit its use in wide ranges of working conditions. To be able to tackle hunting problem efficiently, works has to be done at the designing of solar-boosted heat pump. DOH of a system, given a certain evaporator time lag, depends largely on the orifice capacity. A larger capacity orifice introduces greater DOH. Therefore, the use of a smaller capacity orifice may be introduced in solar-boosted heat pump.

The advantages of using a smaller capacity orifice are quicker responses to rapid change in solar radiation and smoother working pressures. However, trade-offs of using this orifice are higher DSH at high solar radiation and more energy consumption.

Reducing the evaporator time lag by reducing evaporator tube length is not an easy option. The evaporator in this application is the solar collector. The area of evaporator plates is fixed, given a certain solar radiation at a particular location. Evaporator tubes have to be well distributed over the area to maximise heat gain from the solar radiation.

Changing TEV sensor bulb location is also another option to reduce evaporator time lag. However, this method depends on two factors; length of sensor capillary tube and installation of solar-boosted heat pump water heater. The evaporator plates are usually installed on the roof, which is far away from the water tank and compressor. Attempt to place the sensor bulb anywhere close to the evaporator is not likely because the capillary tube length is limited by the TEV manufacturer, to be generally not longer than 2 meters.

5 SUMMARY

Refrigerant flow instability in solar-boosted heat pump has been experimentally studied. This flow instability problem is attributed to inappropriate thermostatic expansion valve selection, long evaporator tubes, and rapidly changing solar conditions. Experiments showed that the flow instability increased at lower solar radiation. A larger capacity orifice introduced more instability. Therefore, it is purposed that using a smaller capacity orifice can reduce the flow instability.

A new measure for the flow instability, DOH, was also introduced in this study. DOH is the percent difference between the maximum and the minimum refrigerant mass flow rate. It was found that a greater capacity orifice presents a larger DOH.

Hunting does not always reduce system efficiency. In some cases, such as in this study, about 5% of energy can be saved in a system that has a hunting phenomenon??

6 NOMENCLATURE

DSC - degree of subcooling [K]
DSH - degree of superheating [K]
DOH - degree of hunting [%]
Pei - pressure at evaporator inlet [kPa]
Peo - pressure at evaporator outlet [kPa]
Pci - pressure at condenser inlet [kPa]
Pco - pressure at condenser outlet [kPa]
T - temperature [K]

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