Development of a steam jet refrigeration cycle for the actual application driven by low grade thermal energy

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Abstract

The aim of this paper is to develop the jet refrigerator and test it under the actual ambient condition in Thailand. The prototype steam jet refrigerator with a cooling capacity of 3000W is newly designed and constructed. It is driven by low grade thermal energy. In this case, the LPG burner is used to simulate the heat source for driving the boiler. The geometries of the ejector are fixed throughout the test. Two primary nozzles with its throat diameter of 3.3 and 3.8 mm are used to test the system performance. They produce the nozzle’s exit Mach number of 4. The refrigerator is used to produce the chilled water at various cooling load. The results indicate that the prototype jet refrigerator can completely be operated at the actual ambient condition in Thailand where the cooling water temperature produced by cooling tower is between 29 and 33°C. The maximum COP of 0.45 is achieved when the refrigerator is operated at boiler temperature of 110°C, evaporator temperature of 17°C, and cooling capacity of 3000W.

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Keywords: Air-conditioning, Jet refrigeration cycle, Jet cooling, Solar-cooling, Ejector

1. Introduction

Nowadays, the most widely used refrigeration system for air-conditioning in the household sector and buildings are a vapour compression system. This system essentially requires electrical energy to produce the useful refrigeration. This is because such systems must be driven by means of a mechanical

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compressor. As a result, green house gas (GHG) emission that is generated during electricity generation is released increasingly to the environment. This reflects the fact that refrigeration and air-conditioning systems are one of the high emitters of GHG to the environment.

To reduce the demand of electricity for refrigeration application, alternative refrigeration systems that can be operated by using thermal energy, heat-powered refrigeration cycle, is introduced at present time [1, 3, and 9]. This cycle can be powered by low-grade thermal energy as low as 90-130°C [1-9]. This kind of energy is usually available from renewable resources or waste-heat rejected from industrial processes. Therefore, the electricity is not required for producing useful refrigeration. A reduction in GHG emission is a consequence.

Jet refrigeration system, which is one of the heat-powered refrigeration cycles, is of current interest [1-14]. The distinctive point of such cycle is that it is relatively simple to design, construct and operate compared to the other types of heat-powered refrigeration systems [1]. In this cycle, the important equipment known as an ejector is used as a main driving part for the system. This is because an ejector is used to elevate refrigerant pressure similar to the use of a mechanical compressor [1].

The components of an ejector are shown in Fig.1 and the schematic diagram of a jet refrigeration system is shown in Fig.2. Referring to Fig.1, as high pressure steam from the boiler, known as a primary fluid, is accelerated passing through the primary nozzle. A supersonic jet stream of the primary fluid is produced within the mixing chamber. Very low pressure region at the mixing chamber is obtained as a consequence. This low pressure region can draw secondary fluid from the evaporator (where the refrigeration effect is produced) into the mixing chamber. The primary fluid and the secondary fluid then mix together within the mixing chamber. Due to high momentum of the primary fluid, the mixed stream is still in form of the supersonic flow. At the end of the throat section, due to the large difference in pressure between mixed stream and back pressure (condenser pressure), the series of oblique shocks are thought to be induced [6]. The shock causes a major compression effect to occur and flow form is suddenly changed from supersonic to subsonic. A further compression of the flow is achieved as it is brought to stagnation through a subsonic diffuser. The ejector is discharged at a pressure (back pressure) equal to the saturation pressure in the condenser. A significant parameter used to indicate the performance of an ejector is the entrainment ratio:

\[
R_m = \frac{\text{mass flow rate of secondary fluid}}{\text{mass flow rate of primary fluid}}
\] (1)

For jet refrigeration system referring to Fig.2, an ejector entrains a low pressure saturated vapour from the evaporator, where the refrigeration effect is produced, as the secondary fluid. It uses a hot and high pressure vapour from the boiler as the primary fluid. The ejector discharges its exhaust to the condenser where the fluid is condensed to liquid by rejecting heat out to the surroundings. Performance of a steam jet refrigeration system is defined in terms of the Coefficient of performance (COP):

\[
COP = R_m \frac{h_{g@\text{evap}} - h_{g@\text{cond}}}{h_{g@\text{boiler}} - h_{g@\text{cond}}}
\] (2)

Where, \( h_{g@\text{evap}} \) is the enthalpy of the saturated vapour at the evaporator (kJ/kg)
\( h_{g@\text{boiler}} \) is the enthalpy of the saturated vapour at the boiler (kJ/kg)
\( h_{g@\text{cond}} \) is the enthalpy of the saturated liquid at the condenser (kJ/kg)

Usually, the enthalpy change at the evaporator is approximately equal to the enthalpy change at the boiler [1, 4], and therefore, the COP can be defined as:
According to the literature survey [8-14], it is found that most of the jet refrigeration cycle is tested experimentally based on the Lab-scale. Very few literatures in which the jet refrigeration cycle is tested at the actual application (used for actual air-conditionings) are found. In addition, it is also found that the existing jet refrigerator is tested at low ambient temperature where the cooling water produced by commonly used cooling tower is relatively low (17-20°C) [11-13] compared to ambient temperature of Thailand (28-33°C). This is a critical point for designing the jet refrigerator to be used for the actual ambient condition in Thailand.

The aim of this paper is to develop the jet refrigerator and test it under the actual ambient condition in Thailand. The prototype steam jet refrigerator with a cooling capacity of 3000W is newly designed and constructed. It is driven by low grade thermal energy. In this case, the LPG burner is used to simulate the heat source for driving the boiler. The geometries of the ejector are fixed throughout the test. Two primary nozzles with its throat diameter of 3.3 and 3.8 mm are used to test the system performance. They produce the nozzle’s exit Mach number of 4. The refrigerator is used to produce the chilled water at various cooling load. In such case, a 3 kW electric immersion heater is used to simulate the cooling load. A condenser is cooled by the cooling water produced by a commonly used cooling tower. The results indicate that the prototype jet refrigerator can completely be operated at the actual ambient condition in Thailand where cooling water for a condenser is between 29 and 33°C. It also shows that when the primary nozzle, 3.8M4, is used, it provides the maximum COP. In such case, the maximum COP of 0.45 is achieved when the refrigerator is operated at boiler temperature of 110°C, evaporator temperature of 17°C and cooling capacity of 3000W.
Fig. 3. The schematic diagram of the prototype steam jet refrigerator

Fig. 4. The significant dimension of the ejector and primary nozzle used for testing the refrigerator
2. The prototype of the steam jet refrigerator

Fig. 3 shows the schematic diagram of the prototype steam ejector refrigeration cycle. It consists mainly of the steam-boiler, evaporator, ejector, condenser and pumping system. All components were fabricated from stainless steel, brass and polymer. The Argon-TIG welding technique was used in order to assemble all stainless steel vessels. Mixing chamber, throat, subsonic diffuser and primary nozzle were made up of brass. All valves and fittings used in the system were manufactured by stainless-steel and fittings used were compression fitting type. Stainless-steel tubes were used for piping work to link all components together. The steam-boiler consists of two components which are steam boiler and steam separator. The steam-boiler shell was fabricated from a 5-inch, 50 cm long, stainless steel pipe, with two flanges welded at the top and the bottom. The mixed steam and liquid in the top part of boiler is separated at the steam separator. It was fabricated from a 4-inch, 40 cm long, schedule 40s stainless steel tube. To prevent the heat loss between boiler’s vessel and surroundings, the boiler was well-insulated by glass-fiber wool covered by aluminum foil. The LPG burner was used to generate the heat for producing the steam. The steam produced by the boiler is used as the primary fluid for the primary nozzle.

The evaporator vessel was made up of 4-inch stainless steel pipe. In order to promote the refrigeration effect, the 10 baffles were fitted along the evaporator column. The working fluid within the evaporator was circulated using magnetic-coupling pump to promote the refrigeration effect. A 3000W electric immersion heater used together with variable transformer was used to produce the cooling load. It was installed within the insulated box which the water is contained inside. A cooling load was transferred to the working fluid within the evaporator via a plate heat exchanger. Therefore, the chilled water produced by this refrigerator is directly related to the evaporator temperature. To prevent the heat loss and gain between evaporator’s vessel and surroundings, it was well-insulated by neoprene foam.

The condenser was modified from three plate heat exchangers. They were connected together in parallel. The cooling water produced by a commonly used cooling tower was used to absorb heat from the working fluid and was then rejected to the surroundings. The working fluid condensed from the condenser was accumulated within the receiver tank. It was then pumped back to the boiler and evaporator by means of a pneumatic diaphragm pump.

The ejector and primary nozzle used were fabricated by brass. They were designed based on compressible flow theory recommended by literature [4]. The significant dimension of the ejector and primary nozzle is shown in Fig 4.

Type-k thermocouple with the accuracy of 0.5°C was used to measure the temperature at the point of interest. The pressure inside the boiler, evaporator, and condenser were detected using the pressure transducer and pressure gauge. The level of the working fluid of all vessels can be observed using attached sight glass. In case of protecting the system, the relief valve was installed at the steam boiler to limit pressure inside the vessel.

3. Results and discussions

3.1. Variation of the evaporator temperature with the cooling capacity

Fig. 5 shows the variation of the evaporator temperature with an increase in the cooling capacity after the steady state is reached. In this case, the primary nozzle, 3.8M4, is used to investigate. The boiler temperature is varied between 110°C and 120°C. During the test, the chilled water used for cooling the condenser is varied between 29 and 33°C.
According to the Fig. 5, it can be seen that with the fixed boiler temperature, the evaporator temperature is increased with cooling capacity. The refrigerator can provide the lowest evaporator temperature of 5°C at the cooling capacity of 500W and the maximum evaporator temperature of 17°C at the cooling capacity of 3000W. This evaporator temperature range can be used properly for air-conditioning system [9, 11]. The reason of an increase in evaporator temperature with cooling capacity is that at higher cooling capacity, the larger amount of refrigerant within the evaporator (secondary fluid) is produced. This causes the pressure within the evaporator to increase. Thus, the saturation evaporator temperature is also increased. When the boiler temperature is increased from 110°C to 120°C, the similar result is obtained as can be seen in Fig. 5. It is found obviously that at the same cooling capacity, it produces the same evaporator temperature when the boiler temperature is changed. This is because a suction pressure of the ejector is independent of the boiler temperature. A suction pressure of the ejector depends only on the designed primary nozzle’s exit Mach number that agrees well with the compressible flow theory [4]. It reflects the fact that in order to achieve a better performance for one particular primary nozzle, the refrigerator should be run at relatively low boiler temperature.

Fig. 6. Variation of the evaporator temperature with a cooling capacity.
Fig. 6 shows the results that are tested by the primary nozzle, 3.3M4 and 3.8M4. In this case, the boiler temperature is kept constant at 120°C. It can be seen from the Fig. 6 that with a fixed cooling capacity, the evaporator temperature is independent of the primary nozzle used. This is because both primary nozzles are designed to produce the same nozzle’s exit Mach number. As a result, both primary nozzles can produce the same suction pressure. Therefore, the refrigerator with the use of these two primary nozzles can provide the same evaporator temperature when the cooling capacity is fixed. This implies that the primary nozzle with a fixed nozzle’s exit Mach number which is used for the jet refrigerator does not affect the ability of producing the refrigeration effect.

3.2. Variation of the coefficient of performance with the cooling capacity

In order to analyze the system performance of the jet refrigerator, the well known term, the coefficient of performance (COP), is necessary to know because it indicates the overall performance of the refrigerator. The coefficient of performance of the jet refrigerator can be defined by equation (4).

\[
\text{COP} = \frac{\dot{Q}_{\text{cooling}}}{\dot{Q}_{\text{boiler}}}
\]

where, \(\dot{Q}_{\text{cooling}}\) is the cooling load produced at the evaporator

\(\dot{Q}_{\text{boiler}}\) is the heat supplied to the boiler

The heat supplied to the boiler can be calculated by equation (5).

\[
\dot{Q}_{\text{boiler}} = \dot{m}_p (h_{g@boiler} - h_{f@cond})
\]

where, \(h_{g@boiler}\) is the saturated vapour enthalpy produced by the boiler (kJ/kg)

\(h_{f@cond}\) is the saturated liquid enthalpy at the condenser (kJ/kg)

\(\dot{m}_p\) is the primary fluid mass flow rate (kg/s)

In this case, the primary fluid mass flow rate produced by the boiler can be calculated by equation (6).

\[
\dot{m}_p = A \cdot \frac{k}{P_o \sqrt{RT_o}} \left( \frac{2}{k+1} \right)^{(k+1)/[2(k-1)]}
\]

where, \(A\) is the cross section area of the primary nozzle’s throat (m²)

\(P_o\) is the boiler pressure (kPa)

\(T_o\) is the boiler temperature (K)

\(k\) is the specific heat ratio

\(R\) is the ideal gas constant (kJ/kg.K)

Fig. 7 shows the variation of the COP with an increase in the cooling capacity when the primary nozzle, 3.8M4, is used to test. The boiler temperature is varied between 110°C and 120°C. The value of COP is obtained from equations (4), (5), and (6).
It can be seen from Fig. 7 that with a fixed boiler temperature the COP of the jet refrigerator is increased linearly with an increase in the cooling capacity. The lowest COP for the test is of 0.03 for the cooling capacity of 500 W. Meanwhile, the highest COP of 0.45 is obtained at the cooling capacity of 3000 W. An increase of COP with cooling capacity is the result of an increase in cooling capacity while the heat supplied to the boiler is kept constant due to a fixed boiler temperature. Therefore, COP of the jet refrigerator is increased with cooling capacity. However, it comes together with an undesired cooling temperature, due to an increase in the evaporator temperature.

When the boiler temperature is increased from 110°C to 120°C as can be seen in Fig. 7, with a fixed cooling capacity, a decrease in the COP is found. This is due to the fact that at the higher boiler temperature, the higher heat load supplied to the boiler is required while the cooling capacity is constant. This causes the COP of the refrigerator to drop when the boiler temperature is increased. This implies that for one particular cooling capacity, the jet refrigerator should be operated at relatively low boiler temperature. However, if the boiler temperature is too low, it may cause the malfunction mode of the jet refrigerator due to an inadequate boiler pressure for producing the nozzle’s exit Mach number of 4. As a result of this effect, the ejector is not able to draw a secondary fluid from the evaporator [4].

Fig. 8 shows the variation of the COP with an increase in the cooling capacity when the primary nozzle, 3.3M4 and 3.8M4, are used to test. The boiler temperature is fixed at 120°C throughout the test.

At fixed cooling capacity, it can be seen from Fig. 8 that when the primary nozzle used is changed, the COP also varies significantly. In such case, if the larger primary nozzle’s throat is used, it provides lower COP than that of the case of using smaller one. With the use of larger primary nozzle’s throat, the larger amount of primary fluid mass flow rate produced by the boiler is allowed to pass through the primary nozzle. This causes the heat supplied to the boiler to increase. At the same time, when the cooling capacity is kept constant, a reduction in COP is a consequence. Therefore, with a fixed boiler temperature, the use of a smaller primary nozzle is preferred.
However, the use of a smaller primary nozzle may cause the malfunction of the ejector’s operation due to a decrease in total momentum of the mixed fluid within the ejector. In such case, lower temperature of the cooling water is needed to cool down the condenser. Therefore, the jet refrigerator may not be workable with the actual ambient condition in Thailand.

4. Conclusions

The prototype steam jet refrigeration cycle driven by low-grade thermal energy is developed for testing at actual ambient condition in Thailand where the cooling water produced by cooling tower is between 29 and 33°C. It is found that the prototype steam jet refrigerator can completely be operated with various range of the operating-condition and primary nozzle used which is suitable for air-conditioning system (chilled water produced by refrigerator between 5°C and 17°C). The refrigerator can provide the maximum COP of 0.45 at the cooling capacity of 3000W, evaporator temperature of 17°C and boiler temperature of 110°C.

Acknowledgement

This research is financed by The Thailand Research Fund (TRF). The first author would like to thank the Joint Graduate School of Energy and Environment (JGSEE) for offering the scholarship.

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