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WASTE HEAT RECOVERY BY USING EJECTOR TECHNOLOGY

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Abstract - *Developments of industries and increase in population and higher living standards have caused a great demand of energy, and consequently energy shortage and higher prices, as well as global environmental problems. This forces researchers to turn to renewable energy alternatives and raises voices for seeking approaches of utilizing low grade energies. In the refrigeration field, the ejector refrigeration systems provide a promising way of producing cooling effect by harvesting waste heat from industrial process and automobile or using renewable energy, such as solar radiation and geothermal energy, which makes such systems particularly attractive in this energy-conscious era. They also have some other remarkable merits, such as, using no-moving parts which make them vibration-free, being simple and reliable, having low initial and running cost with long lifetime, and providing the possibility of using environmentally friendly refrigerants. The ejector has also been extensively incorporated into other refrigeration systems, like the sorption systems and vapor compression systems, in order to achieve better system performance and higher energy efficiency. However, the ejector refrigeration systems have relatively low efficiency and difficulty in their design, which greatly limit their widespread in commercial sector, and consequently a number of researches have been done to understand their working characteristics and to improve their performance and promote their use.*

Key Words: Ejector, Boiler, Condenser, Evaporator, Pump, Expansion Device

1. INTRODUCTION

Many industrial processes produce large amounts of excessive heat that is not utilized. The waste heat driven ejector cooling cycle is a very promising approach to utilize low-grade energy for cooling purposes. Much research has been carried out in order to study and improve the vapor jet ejector cooling system (ECS). The main focus of the research conducted are the refrigerants used, the operating conditions, and the characteristic dimensions of the ejector. The main requirements for the working fluid of a vapor jet ejector cooling cycle are its performance as well as its low environmental impact. Roman and Hernandez (2011) compared various refrigerants on their feasibility and performance as a working fluid in an ECS. In their numerical investigation, propane was found to give best results, followed by R134a and R152a. Least favorable working fluids reported in this study are butane and isobutene when compared to the previously mentioned refrigerants. Selvaraju and Mani (2006) experimentally investigated the performance of an ECS with various ejector dimensions at different evaporating, condensing, and generator temperatures. Refrigerant R134a was used and various ejector configurations were evaluated. It was reported that for a given ejector set-up optimum operating conditions exist that result in maximum system performance.

In the present study, the waste heat from a diesel-electric generator is utilized as heat input to the ECS. A prototype demonstrator was designed, built, and evaluated. The refrigerant utilized for this system is HFC R134a. The system was experimentally investigated at different ambient conditions. Furthermore, the characteristic dimensions of the ejector were varied in order to identify an optimum configuration that results in maximum system performance.

1.1 Basic working of Ejector

Referring to the basic ejector refrigeration cycle in Figure 1, the system consists of two loops, the power loop and the refrigeration loop. In the power loop, low-grade heat, Qb, is used in a boiler or generator to evaporate high pressure liquid refrigerant (process 1-2). The high pressure vapor generated, known as the primary fluid, flows through the ejector where it accelerates through the nozzle. The reduction in pressure that occurs induces vapor from the evaporator, known as the secondary fluid, at point 3. The two fluids mix in the mixing chamber before entering the diffuser section where the flow decelerates and pressure recovery occurs. The mixed fluid then flows to the condenser where it is condensed rejecting heat to the environment, Qc. A portion of the liquid exiting the condenser at point 5 is then pumped to the boiler for the completion of the power cycle. The remainder of the liquid is expanded through an expansion device and enters the evaporator of the refrigeration loop at point 6 as a mixture of liquid and vapor.

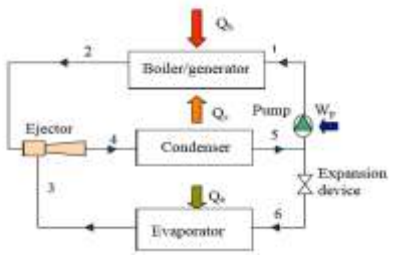

Fig -1: Basic Working

The refrigerant evaporates in the evaporator producing a refrigeration effect, Qe, and the resulting vapor is then drawn into the ejector at point 3. The refrigerant (secondary fluid) mixes with the primary fluid in the ejector and is compressed in the diffuser section before entering the condenser at point 4. The mixed fluid condenses in the condenser and exits at point 5 for the repetition of the refrigeration cycle.

2. PRINCIPLE OF EJECTOR

An ejector, also named as injector, jet pump, thermo-compressor, is a flow device that allows a high pressure primary fluid to accelerate and induce a low pressure secondary fluid into the primary fluid path. As the two fluids mix through a diffuser section, a pressure recovery occurs, which enables the ejector to fulfill the function of a com- presser or a pump. The term “primary” is defined as the driving, motive, or energizing flow for the ejector, while the term “secondary” means the driven, passive, or energized flow. The ejector has a simple structure of four parts: a nozzle, a suction chamber, a mixing chamber and a diffuser, as illustrated in Fig. The flow phenomena inside the ejector are quite complicated and the detailed flow mechanism is not yet quite clear as supersonic flow, shock interactions, turbulent mixing and two-phase flow may involve. The flow patterns inside an ejector may be visualized and analyzed by using optical instruments and computational fluid dynamics (CFD). The main geometry is characterized by the area ratio Ar, which is defined as the area of the constant-area part in the mixing chamber divided by the nozzle throat area.

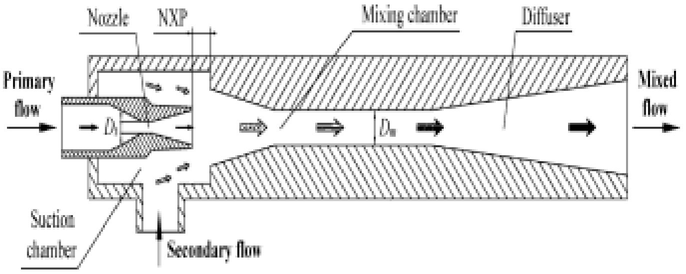

Fig -2: Schematic Drawing of Ejector

2.1. Ejector Pump-

The heart of the ejector-based chiller is the ejector component itself. It operates on the principle of momentum transfer from a high speed supersonic jet to entrain a second, lower-potential flow to create a pumping effect. The operation of an ejector at an idealized on-design condition (defined in Section 2.3.1) is shown qualitatively in Fig, where the variation in pressure and velocity is given at the axial positions indicated in the upper ejector schematic. From axial positions M i, ii, a high-temperature and pressure motive refrigerant flow expands through a converging-diverging nozzle to produce a supersonic jet at the motive nozzle exit. This supersonic flow entrains a suction flow entering from *S ii*. In the ejector mixing section *ii* ,*iii iv*, the motive and suction flows interact and mix until the combined flow nominally reaches a supersonic velocity. At *iv*, the flow must adjust to conditions at the ejector outlet, producing a set of shocks depicted in Fig. as an idealized normal shock at *iv*, before the beginning of the diffuser at *v*. From *v* ,*vi*, pressure is recovered as the total flow decelerates to a low velocity at the ejector outlet. The desired compression effect produced by the ejector is the rise in pressure from the suction inlet *S* to the ejector outlet *vi*. 4 The two critical sections are the motive nozzle and the mixing section. Conditions inside the motive nozzle dictate the flow geometry of the motive jet and determine whether or not there is two-phase flow in applications using refrigerants. Interactions between the motive and suction flows inside the mixing section dictate the overall performance of the ejector

2.2 Motive nozzle-

The flow behavior inside the motive nozzle changes based on the relative magnitudes of the inlet and outlet pressures at states *M* and *ii* in Fig. At a zero difference between the inlet and outlet pressures, there is no flow through the nozzle. As the outlet pressure drops, the flow rate through the nozzle increases, and the pressure of the fluid along the length of the nozzle decreases as it accelerates through the converging part of the nozzle, and rises as it decelerates through the diverging part of the nozzle. This is normal subsonic behavior. But as the back pressure is decreased past a critical point, sonic velocity is achieved at the nozzle throat where the flow chokes, and a further decrease in outlet pressure does not change the flow rate through the nozzle. The flow in the divergent section accelerates until it either shocks before the exit of the nozzle (in which case the fluid will exit the nozzle at a subsonic velocity), or if the outlet pressure is low enough, continues to accelerate for the entire length of the divergent section and exits the nozzle as a supersonic jet. The latter case explains the nominal operating condition for the motive nozzle flow. Under these conditions, many interesting phenomena occur at the nozzle exit depending on the back pressure present there. The specifics of these phenomena are explained in detail in Section.

When operating with a refrigerant, as is of interest in this work, additional complications arise when the flow has the potential to condense or evaporate inside the nozzle. If the expansion inside the motive nozzle is extreme enough, the thermodynamic state of the flow can enter the saturation dome, or exit the dome and become superheated. But since the expansion experienced in such a nozzle is at high transonic velocities, the residence time of the flow at a given condition is similar to the time needed for the kinetics of liquid drop formation or evaporation as such, the flow may exit the motive nozzle in a supersaturated state, making it necessary to consider the influences of metastable states on the motive flow. The complexities of metastable states and two-phase flow make a direct understanding of this type of flow difficult, especially for fluids other than air. Methods are developed in this work to predict flow conditions using a combination of two models: one assuming that the flow behaves as an ideal gas with no phase change, and another that assumes the flow reaches full thermodynamic equilibrium instantly with the associated quality if inside the saturation dome, The real flow conditions lie somewhere between those predicted by these two models, and a condensation shock marks the transition from one flow model to the next in the case of a condensing flow. Across a condensation shock, there is a sharp rise in pressure and temperature as droplets form, and conditions after the shock more closely resemble equilibrium conditions. With this, the likelihood of condensation at the entrance of the mixing section can be assessed and used to explain potential changes in ejector performance.

2.3 Mixing Section-

The high-velocity motive jet exiting the motive nozzle enters the mixing section (defined here to be the constant-area section where the motive jet first comes into contact with the suction flow) and transfers momentum to the suction flow through a jet boundary shear layer. Inherent to this process is a large velocity and temperature mismatch between the motive and suction flows that results in viscous losses and heat transfer, as well as multiple irreversible oblique shocks in the motive jet and diffuser. These flow characteristics are together responsible for the typically low ejector efficiency. In addition to all of these effects is the highly unknown contribution of phase change and its influence on heat and momentum transfer characteristics.

The mixing section is the region of the most complicated flow phenomena. A mixing section can be designed to have a constant-area or constant-pressure geometry, or a combination of both. The constant-pressure mixing section is designed such that the average static pressure within the mixing section remains constant, yielding better ejector performance Unfortunately, they are difficult to design, model, and fabricate; therefore, the majority of ejector studies, including this work, use constant-area mixing sections.

The motive stream typically enters the mixing section at a supersonic velocity and forms a supersonic jet. In general, the ratio between the motive nozzle outlet pressure and back pressure determines the basic geometry of the motive jet flow in the mixing section. If the motive jet is over expanded such that the nozzle outlet pressure is less than the back pressure (back pressure effectively being the suction nozzle outlet pressure, state *ii* in Fig. the jet converges at the motive nozzle exit, where the first set of jet flow features are 7

Oblique shocks issuing from the motive nozzle outlet, as in the top of Fig. However, if the motive jet is under expanded, the outlet pressure exceeds the back pressure, resulting in a jet that diverges at the motive nozzle exit and forms an initial expansion fan at the motive nozzle exit, as in lower part of Fig. Depending on which case occurs, these expansions and compressions reflect off both the constant-pressure boundary formed at the shear layer between the motive jet and suction flow, and the centerline boundary. This centerline boundary acts much like a solid wall in that any compression or expansion incident upon it is reflected as a wave of the same family under perfectly symmetric conditions. But the opposite is true at the boundary of the motive jet. This boundary acts as a constant-pressure boundary, and reflected waves are of the opposite family This reflection of compression and expansion waves occurs many times, but eventually fades as the jet interacts with the suction flow through turbulent mixing and the development of a pressure equilibrium to the point where the flow at the mixing section exit is ideally uniform. The result is a characteristic oscillation in static pressure along the centerline of the mixing section as the jet equalizes to an intermediate condition between the motive and suction inlet states.

3. CONVENTIONAL EJECTOR REFRIGERATION SYSTEM

Fig shows the conventional ejector refrigeration system and the P–h diagram with two ejector models which are extensively used in refrigeration technology, namely constant- area mixing model and constant-pressure mixing model. The working processes of the system is generalized as: low-grade energy (Q_g) is delivered to the generator for vaporization (g, i—go). The high pressure vapor from the generator, i.e. the primary flow, enters into the ejector nozzle and draws the low pressure vapor from the evaporator, i.e. the secondary flow. The two flows undergo mixing and pressure recovery in the ejector (g, o& e, o — c, i). The mixed flow is then fed into the condenser (c, i — c, o), where it is condensed by rejecting heat to the environment (Q_C). The liquid from the condenser is divided into two parts. One part goes through the expansion device (c, o — e, i), and then enters into the evaporator (e, i — e, o) to produce the refrigerating effect (Q_e). The rest liquid is pumped back to the generator via the circulation pump (c, o — g, i), and completes a circle.

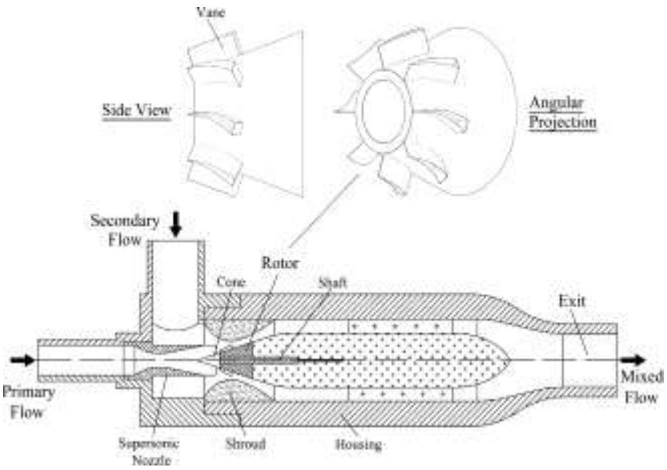

Fig -3: Conventional Ejector Refrigeration System

Various methods have been used to study the working character- is tics of the ejector refrigeration system. Mathematical simulation is a simple and quick way to evaluate the system performance. Exergy %to analyze the irreversibility in each component for system optimization. Grey system theory provides another option for system analysis. Experiment are always irreplaceable and results indicated that such system have high potential for wide use.

3.1. System performance-

The operating condition in generator, condenser and evaporator are determining by heat source, heat sink, and the refrigerating purpose, respectively. The system COP is expressed as:

$$COP = \frac{Qe}{Qg + Wpump}$$

The power of the pump(Wpump) is typically less than 1% of the heat load in the generator (Qg) Therefore, it can be neglected in the calculation of COP.

$$COP = \frac{Qe}{Qg + Wpump} = \frac{\dot{m}_s (h_{e,o} - h_{e,i})}{\dot{m}_p (h_{g,o} - h_{g,i})}$$

3.2 Working Fluids-

It is obvious from Eq. the system COP depends on both the entrainment ratio μ and refrigerant properties, thus selection of the working fluid is essential in the ejector refrigeration system. Summarizes the working fluids used in the conventional ejector refrigeration system Results show that use of mixture refrigerant does not always improve the system performance, an appropriate refrigerant not only can enhance the system efficiency, but also is crucial for the ejector operation. Moreover, the working fluid can be classified into dry fluid, wet fluid and isentropic fluid. The dry fluids are more favorable in the conventional ejector refrigeration systems.

4 ADVANCED EJECTOR REFRIGERATION SYSTEM

Since the conventional ejector refrigeration system, has a relatively low COP, researchers have tried to find more advanced ejector refrigeration systems with higher COP by means of simulations and experiments. Attempts in this respect have been made in the follow ways: changing ejector configurations, introducing multi-stage ejectors, eliminating the mechanical pump, and using a regenerator and/or a pre-cooler.

4.1 Improved ejector structure

It is known that the ejector geometric structure greatly affects its performance. For example, the nozzle position impacts the system COP and cooling capacity, and an ejector with a spindle to vary the primary throat area in the nozzle can provide fine tuning and flexibility for its operation. Using a movable nozzle or adding a movable spindle is relatively easy and effective to optimize the ejector performance. To improve the efficiency of mixing process, a pressure-exchange ejector and different nozzle structures have been proposed.

A novel supersonic rotor-vane/pressure-exchange ejector was proposed by Hong et al. to enhance ejector efficiency, which is shown in fig. A supersonic flow from the nozzle produces an attached weak shock on the apex of a stationary conical fore-body. The flow is diverted over the canted wedge-shaped vanes and expands at the rear of the vane, drawing the secondary flow into interstices behind the vane and into contact with the primary fluid. The rotating interfaces behind the vanes offers the medium through which pressure exchange takes place. Since the rotating interfaces benefit pressure exchange and the rotor vanes are canted, the rotor spun freely and nearly frictionless and a higher efficiency might be obtained.

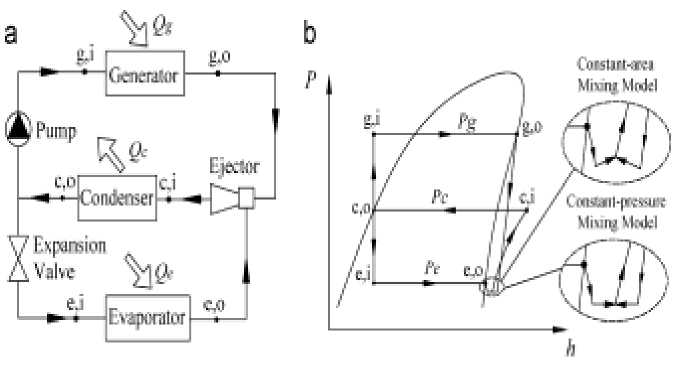

Fig -4: Rotor Vane Pressure Exchange Ejector

4.2 Multi-ejector refrigeration system-

It is difficult for a single stage ejector to keep the system running at optimum condition because of the critical back pressure This motivates researchers to solve this problem by using multi-pressure ejector refrigeration system. A two-stage ejector consisting of a traditional first stage without diffuser and an annular second stage directly located at the outlet of the first stage mixing chamber schematically describes such ejector structure and whole system as well as it's P-h diagram. The vapor from the generator is divided into two parts to enhance the ejector performance, both acting as the primary flow for different secondary flows in the two-stage ejector. The processes in the first stage are exactly the same as these of the regular ejector; partial vapor from the generator (mg) goes into the ejector and entrains the secondary flow from the evaporator

The exhaust vapor from the first stage is directly fed into the second stage as the secondary flow. The rest of the vapor from the generator (mg″) acts as another primary flow for the second stage and mixes with the exhaust and the mixed flow finally enters into the condenser. The remaining process are the same as these in the conventional ejector refrigeration system.

The ejector refrigeration system can be constructed with several ejector in a parallel arrangement fig. shows three ejector placed in parallel before the condenser One ejector operated at a time and the operation of each ejector is determined by the condenser pressure (pc)Ejector 1

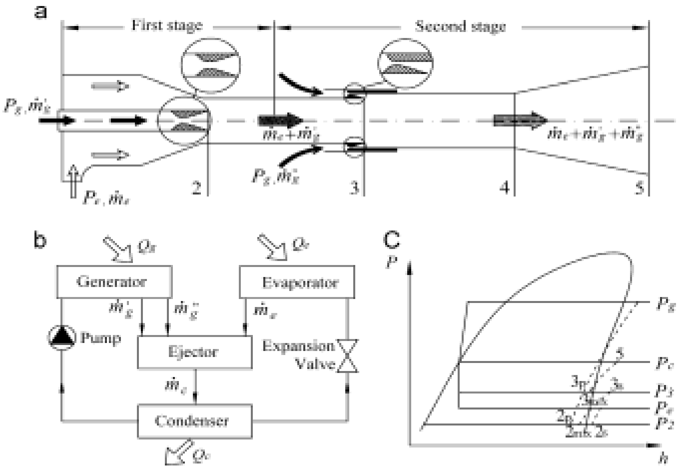

Fig -5: Two Stage Ejector Refrigeration System

operates at a condenser pressure below (pb1)when the condenser pressure in between (pb1)and (pb2) ejector 2 would be working and ejector 3 operates at pc>pb2 This multi ejector has no back pressure pb* and can avoid sudden performance drop in a fixed geometry ejector and is therefore able to work at optimum condition for a wider range of condenser temperature.

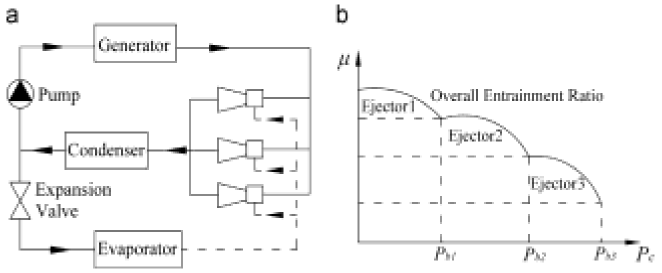

Fig -6: Three parallel multi-ejector refrigeration system

5. CONCLUSION

A basic background and development of an ejector and its application in refrigeration purposes. At this moment, it can be said that the understanding in ejector theory has not been completely cleared. Even though these simulated results were claimed to become more accurate than others, very few of them were experimentally verified and approved. An ejector is the critical component of a jet refrigeration system. Not only the system operating conditions, but two parameters, used to express the system performance (entrainment ratio and critical pressure), were also found to directly depend on ejector geometries and its working fluid. Many recent studies proposed and tested some new criterion in designing an ejector which has higher pressure lift performance. Halocarbon refrigerants seem to be a practical and appropriate working fluid for jet refrigeration system. Compared to the water system, the halocarbon refrigerator can provide higher performance and the required heat source temperature is lower. Therefore, the low grade energy, such as a solar energy, can be utilized and drive the system. Even though, the jet refrigerator has suffered from its very low COP, the improved COP from combining ejector to other types of refrigeration system (vapor compression and absorption system) was remarkable. It is hoped that this contribution will stimulate wider interest in the technology of ejectors and their applications in refrigeration system. It should be useful for any newcomer in this field of technology.

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