論 文 の 内 容 の 要 旨

論文題目 Study on performance characteristics of gas-ejector applied for solar ejector air-conditioning system
（太陽熱エジェクタ空調に用いるガスエジェクタに関する研究）

陳　作舟

Solar co-generation system is promising in solar energy utilization for building air-conditioning. Heat and electricity could be generated simultaneously by a solar co-generation system for air-conditioning system. To effectively convert solar heat into cooling effect, ejector refrigeration system has been proposed and studied. Ejector refrigeration system is a heat recovery refrigeration system using ejector as its key part to create cooling effect, which is cost-saving and eco-friendly. However, as solar heat is unstable, it is impractical to obtain stable cooling effect using a fixed geometry ejector. Variable geometry ejector has been further proposed to regulate capacity of the ejector refrigeration system. Still, as unstable solar energy is adopted to drive the ejector, the operating process inside the ejector is complex. To design a practical solar-powered ejector refrigeration system, it is necessary to obtain a comprehensive understanding of the supersonic flow and mixing process inside the ejector.

An ejector comprises of a nozzle and a mixing chamber, the high pressure driving flow enters the mixing chamber from the nozzle, and will be converted to a fast flow with low pressure. Meanwhile, the suction flow is entrained into the mixing chamber by the pressure difference, and flow in the space between the driving flow boundary and the mixing chamber wall. Part of the kinetic energy is transferred from the driving flow to the suction flow inside the mixing section. The suction flow is therefore accelerated and pressurized. In effect, the ejector functions as a compressor in the ejector refrigeration system, which enables heat to function as the driving energy. By intruding a needle inside the nozzle throat, the driving flow rate could be regulated by the nozzle throat area variation, the ejector working capacity could therefore be adjusted when the input energy is unstable. There exists an optimum nozzle opening to maximize the suction flow rate for each operating condition.

As the driving flow is converted to a supersonic flow by the nozzle, Mach waves occur and affect the boundary development of the driving flow, as well as the process of kinetic energy transfer to the suction flow. Therefore, the variable nozzle configuration has become a factor that can affect the ejector performance. Proper nozzle configuration contributes to the ejector performance enhancement. In the currently research, experimental investigation has been conducted on the variable geometry ejector performance. By regulating a needle location, the optimum performance of variable geometry ejector was tested in a range of generating temperature between 60 °C to 80 °C, the evaporating temperature was set to 20 °C, and the condenser temperature varied from 30 °C to 45 °C. In addition, both the supersonic and subsonic nozzles were adopted in the experiment to discuss the influence of nozzle configuration on the ejector performance. The variable supersonic nozzle has a convergent-divergent tunnel, thus the nozzle configuration changes during the needle regulation. On the other hand, the variable subsonic nozzle has a convergent duct, which could only provide sonic outflow with a constant nozzle configuration. The nozzle opening in the experiment was regulated from 100 % to 40 % for each operating condition. At a low condensing temperature of 30 °C, the variable supersonic nozzle could achieve the highest suction flow rate of 3.85 g/s at the nozzle opening of 53 %, while the variable subsonic nozzle enhanced the suction flow rate up to 4.07 g/s at the nozzle opening of 45 %. The subsonic nozzle obtained higher performance than that of the supersonic nozzle. However, as the condenser temperature was increased to 35 °C, the variable supersonic nozzle offered a highest suction flow rate of 3.29 g/s at the nozzle opening of 73 %, corresponding to the value of 3.10 g/s and 84 % by a variable subsonic nozzle. Based on a nozzle configuration calculation, the highest nozzle efficiency is obtained while the driving flow pressure at the nozzle exit is equal to the suction flow pressure at the ejector inlet. The results indicates that the nozzle configuration has significant influence on the ejector performance. According to the experiment, a supersonic nozzle is appropriate in the occasion with high condensing temperature, while a subsonic nozzle is suitable for the operating condition with low condensing temperature.

Based on the discussion of the nozzle configuration, a performance map related to the generating temperature, nozzle opening and the critical condenser temperature was experimentally drawn to provide information for variable geometry ejector control strategy with unstable heat input. Within the generating temperature range of 60 °C to 80 °C, the nozzle opening was regulated from 100 % to 64 %, the critical condenser temperature and the highest performance of the ejector were experimentally tracked. The results gave a clear description of control strategy for the variable geometry ejector.

Meanwhile, numerical simulation has been conducted to analyze the flow and Mach wave characteristics inside the ejector. The exact ejector dimensions adopted in the experiment was used in the simulation model. Numerical simulation using SST k-ω and ideal gas assumption provides 10 % over-prediction on both the critical backpressure and the entrainment ratio of the ejector, which is considered acceptable for ejector analysis. The velocity contour inside the ejector reveals the Mach wave characteristics inside the driving flow, as well as the effect of nozzle configuration on the ejector performance. As the needle is inserted into the supersonic nozzle throat during the regulation, the throat area decreases with a constant nozzle exit area. As a result, the driving flow could be converted from an under-expanded flow to an ideally-expanded flow during the adjustment, but will become an over-expanded flow is the nozzle opening is too small. Ideally-expanded driving flow enhances the ejector performance mostly, yet once shockwave occurs in the over-expanded driving flow, the irreversible energy losses will have negative influence on the ejector performance. Meanwhile, the subsonic nozzle have a constant nozzle configuration, the driving flow will be always in under-expanded condition. The nozzle opening regulation range is wide with a low condensing temperature, thus the driving flow from a variable supersonic nozzle will inevitably become over-expanded. However, with a higher condensing temperature, it is possible to design an optimized supersonic nozzle to achieve ideally-expanded driving flow at the optimum nozzle opening.

The driving flow expansion process is of importance to the ejector performance, and it is easily influenced by the Mach wave at the nozzle exit. A simulation methodology was proposed to describe the driving flow expansion inside an ejector. The method of characteristics (MOC) was adopted in the current research. The Prandtl-Meyer expansion of the driving flow from the nozzle exit was considered in the model, and a grid was built inside the driving flow region using finite difference method. The simulation results were compared with the isentropic expansion calculation which is widely adopted in the one-dimensional theoretical model for ejector performance evaluation. According the simulation results, an optimized nozzle could produce ideally-expanded driving flow into the ejector, but if the nozzle structure is inappropriately designed, the occurrence of Mach wave will cause extra expansion of the driving flow. The extra expansion will block part of the suction flow region, therefore it has negative influence on the ejector performance. The flow region of an under-expanded driving flow area is more than 130 % of an ideally-expanded flow in the simulation condition. The results indicate that the isentropic expansion calculation of the driving flow may not be capable to provide driving flow region prediction with satisfactory accuracy if variable geometry nozzle as well as unstable heat source are adopted for an ejector refrigeration system. It is necessary to consider the Mach wave in order to correct the driving flow expansion with unstable heat input and changeable nozzle configuration.

The MOC simulation results are further validated by visualization experimental method using a Schlieren system. The Schlieren system is able to capture uneven distributed density in a transparent media, and shows the density distribution by illuminance variation in the Schelieren images. Transparent ejectors were designed and manufactured with rectangular mixing chamber with thin glasses attached to the front and back sides. Nitrogen was adopted as the working fluid, and the driving flow pressure was adjusted from 40 kPa to 60 kPa in the experiment. The supersonic and subsonic nozzles adopted in the variable geometry ejector experiment were tested in the visualization experiment. The driving flow boundary development as well as the occurrence of shockwave could be clearly observed from the images. Expansion exaggeration of the driving flow could be observed as the pressure difference between the driving and suction flow increases. The first Mach cell was taken into consideration, the maximum diameter measured from the Schlieren images were compared with the simulation results. The comparison show that a good agreement was achieved by the method of characteristics. Thus the simulation model using the method of characteristics is capable to obtain the driving flow boundary development in a gas-ejector. It could be concluded that ideally-expanded driving flow create gradual converging tunnel for the suction flow, which is ideal for the ejector performance enhancement, on the other hand, over-expanded driving flow will unnecessarily occupy the suction flow region.

In the current research, a comprehensive discussion has been conducted to the performance of the solar-powered variable geometry ejector, the results are important in understanding the flow and Mach wave characteristics inside the ejector. Which further helps to develop the proper ejector configuration for unstable solar energy utilization. Meanwhile, the experimental investigation has validated that the variable geometry ejector is promising to provide stable performance with unstable heat input. Future studies could be conducted on the general performance of solar-powered ejector refrigeration system, as well as the optimization of the mixing chamber of the ejector. Meanwhile, appropriate refrigerant should be selected to retain a high-efficient and eco-friendly ejector refrigeration system.