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An experimental investigation of steam ejector refrigeration system powered by extra low temperature heat source

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ABSTRACT

A steam ejector refrigeration system is a low capital cost solution for utilizing industrial waste heat or solar energy. When the heat source temperature is lower than 80 °C, the utilization of the thermal energy from such a low-temperature heat source can be a considerable challenge. In this investigation, an experimental prototype for the steam ejector refrigeration system was designed and manufactured, which can operate using extra low-temperature heat source below 80 °C. The effects of the operation temperature, the nozzle exit position (NXP) and the diameter of the constant area section on the working performance of the steam ejector were investigated at generating temperatures ranging from 40 °C to 70 °C. Three ejectors with a same de Laval nozzle for the primary nozzle and three different constant-area sections were designed and fabricated. The experimental results show that a steam ejector can function for a certain configuration size of the steam ejector with a generating temperature ranging from 40 °C to 70 °C and an evaporating temperature of 10 °C. For a given NXP, the system COP and cooling capacity of the steam ejector decreased until inoperative as the diameter of the constant area section reduced. The results of this investigation provided a good solution for the refrigeration application of the steam ejector refrigeration system powered by an extra low-temperature heat source.

1. Introduction

The steam ejector has a history of more than 100 years. It was invented by Charles Peterson as early as 1901 in order to remove air from a steam engine's condenser [1]. The advantages of the steam ejector includes utilizing low-grade thermal energy, using water, an environmentally friendly material, as the working medium, simplicity in construction, reliability in operation and low capital cost. These advantages caused the steam ejector refrigeration system to be widely applied in the air conditioning of large buildings in the early 1930s [2]. However, it was superseded by the vapor compression refrigeration system due to its higher COP, smaller volume and convenient operation. With enhanced environmental protection concerns and the growth in demand for air conditioning and refrigeration in daily life, the steam ejector refrigeration once again has been investigated in research. In theoretical research, Keenan et al. [3,4] first established a one-dimensional model to predict the performance of the ejector based on mass, momentum and energy equation with ideal gas, which ignored friction losses. In the following decades, Munday et al. [5], Huang et al. [6] and Chen et al. [7] improved the one-dimensional model developed by Keenan et al. [3,4]. At the same time, the empirical and semi-empirical correlations were derived based on the experiment results [8–11]. With the rapid development of computational fluid dynamics (CFD), numerical simulation became a popular method to resolve mixing and shock wave problems and to study the effects of steam ejector geometries on the COP in the steam ejector refrigeration system [12–25]. The realizable k-ε model was chosen as the turbulence model to study fluid flow in steam ejectors. In the experimental aspect, Eames et al. [26–28], Sun [29,30], Chen [31], Aphornratana et al. [15,32–34], Dong et al. [35–37], Riffat et al. [38,39], Meyer et al. [2] and Vineet et al. [19] conducted experimental investigations to determine the effects of working temperature, nozzle structure and NXP on the performance of the steam ejector with generating temperatures ranging from 84 °C to 140 °C, respectively. The experiment results contributed by Meyer et al. [2] and Riffat et al. [38] implied that the steam ejector can function at a generating temperature below 100 °C for refrigeration application, and the optimum performance took place at a generating temperature of around 90 °C to 95 °C. In this study, a steam ejector refrigeration system was developed and tested in order to find out whether a steam ejector can function for refrigeration application at an extra low-temperature heat source below

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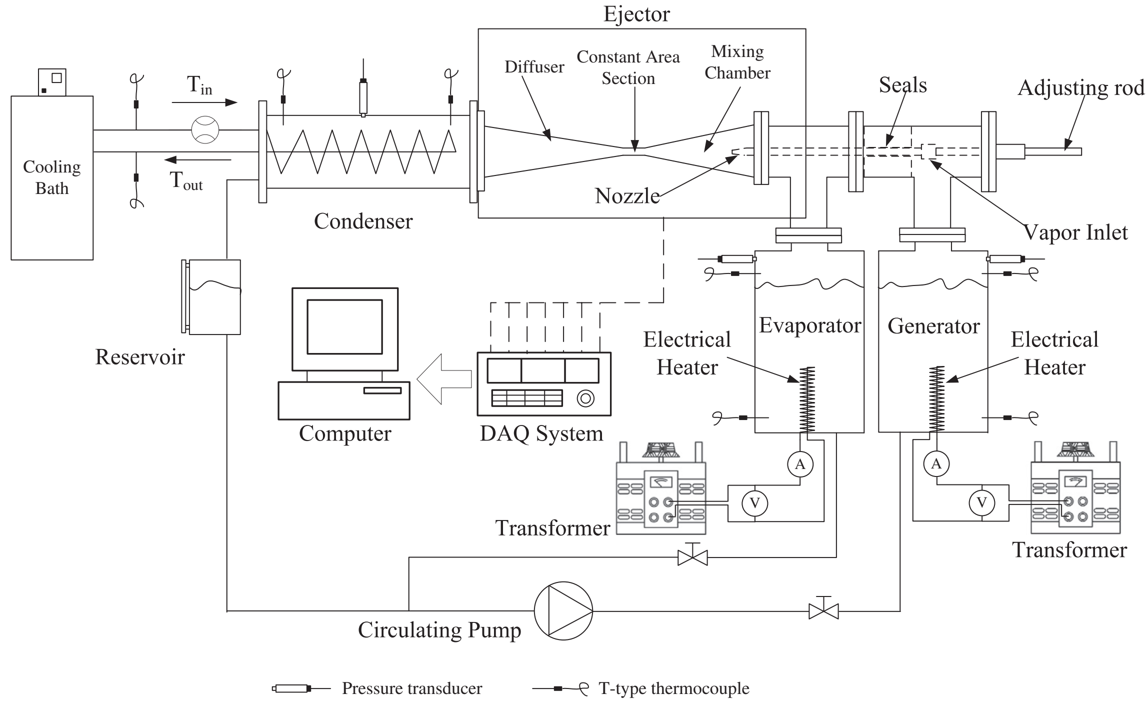

Fig. 1. Schematic diagram of the experimental system for the steam ejector refrigeration system.

80 °C. The effects of the operation temperatures and structure parameters on the working performance of the steam ejector were investigated at generating temperatures ranging from 40 °C to 70 °C.

2. Experimental setup

The experimental system of the steam ejector refrigeration, as shown in Fig. 1, mainly consists of a generator, an evaporator, an ejector, a condenser, a reservoir, a circulating pump, measuring devices, and two electrical heaters. The generator and evaporator were fabricated from a stainless steel cylinder (Φ 273 mm × 1020 mm) with flanges welded on the top. The bottom of each stainless steel cylinder was equipped with an electrical heater. The electrical heaters were used to simulate the low-temperature heat source in the generator and thermal load in the evaporator. For each electrical heater, the maximum heating capacity was 5 kW and the heating power was controlled by means of a transformer. The generator and evaporator were carefully insulated by thermal insulation materials. The condenser was a shell and coil condenser and was cooled by chilled water from a cooling bath. The cooling capacity of the cooling bath was 4000 W at 20 °C. A diaphragm pump was used as the circulating pump.

Fig. 1 also shows the fabricated stainless steel ejector with movable nozzle. The ejector consists of four components, i.e., a nozzle, a mixing chamber, a constant area section and a diffuser. The dimensions of the experimental steam ejector are shown in Fig. 2. The temperatures of the primary and secondary flows were controlled by the power input

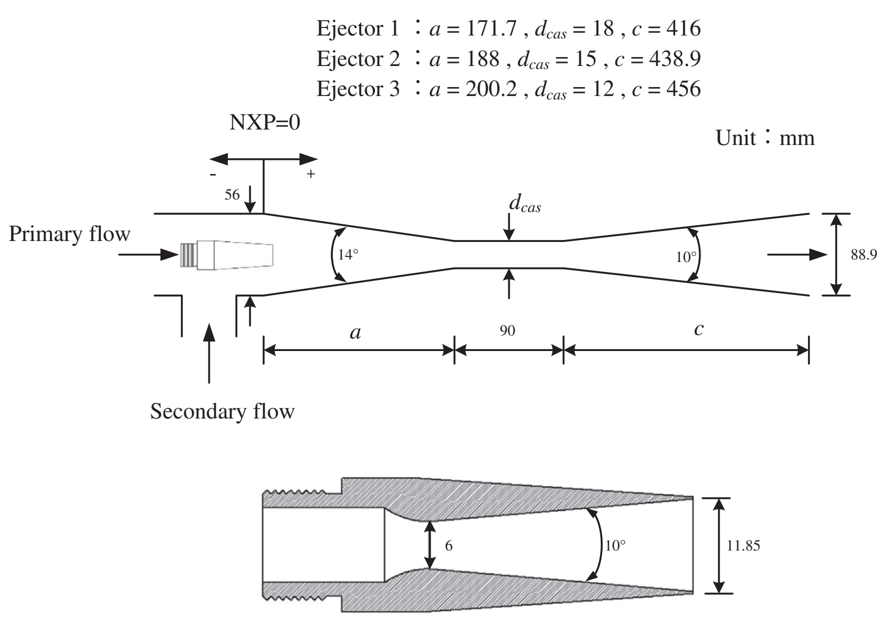

Fig. 2. Dimensions of the experimental steam ejector.