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An experimental investigation into the integration of a jet-pump refrigeration cycle and a novel jet-spay thermal ice storage system

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ABSTRACT

This paper describes and evaluates the results of an experimental investigation in to a novel thermally activated jet-pump refrigerator and a jet spay thermal ice storage system, in which a steam driven jet-pump is used to create a vacuum pressure in a hermetic vessel into which water is sprayed through a nozzle. The effect creates ice in the vessel. It is envisaged that the ice is used as a coolth storage medium for cooling building ventilation air. It is envisaged that the jet-pump refrigerator would be powered by solar heat and so the coolth store would help to level out the peaks and troughs in output experienced by solar powered devices. The paper describes the proposed system and the experimental apparatus and discusses the results.

1. Introduction

The use of thermal ice storage (TIS) systems to balance time-wise variations in the demand for cooling, is not new. Systems have been developed for both air conditioning and drinks coolers. They include machines that continually build an ice layer on refrigerated plates or drums, which is either periodically harvested for ice using scrapers or, using a serpentine refrigerated coil contained within a water bath, simply left to alternately build-up and melt depending on the demand for cooling. Another well documented method is to alternately freeze and melt water sealed within hollow plastic spheres. Known as encapsulated ice storage this method has been commercially available and a subject of research for many years, [1]. Until recently these TIS systems were developed for use with electrically powered vapour compression refrigerator. More recently, however, research has been carried out into the use of solar powered adsorption cycle systems incorporating ice making devices [2,3], and the present authors have investigated the use of thermal ice storage systems with other thermally activated refrigeration machines, such as vapour absorption [4], and jet-pump machines [5].

TIS systems are thought to have been devised for use with electrically powered vapour compression refrigerators primarily to allow users the opportunity to reduce energy costs by storing coolth during off-peak electricity supply times. However, this is not the case for solar powered refrigeration systems for which the energy source is of course supplied at no cost to the user. The use of TIS with solar powered refrigerators is necessary if building cooling is to continue at the normal rate for a reasonable but limited time after the sun disappears from view.

This paper describes a thermally activated jet-pump refrigerator combined with a novel system, which the authors term jet-spray TIS. The paper goes on to describe and evaluate the results of an experimental study in to its energy performance when making ice during the TIS process.

2. A novel jet-pump thermal ice storage system

Fig. 1 shows a schematic view of the proposed system. This is made up from a conventional jet-pump refrigerator and a modified evaporator vessel to permit the production of ice. The jet-pump refrigerator includes a steam generator, an evaporator, a condenser and connections via pipes, heat exchangers, pumps and valves supplying the building and condenser cooling systems and generator heating via a solar-thermal panel. In order to achieve the highest thermal efficiency the condenser should be cooled by water taken from an evaporative cooling tower and the generator should be heated using high pressure hot water from a concentrating type of solar-thermal panel.

Referring to Fig. 1 the system operates as follows: High pressure steam is produced in the generator at a pressure typically

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Nomenclature

COP	coefficient of performance
C_{pf}	specific heat at constant pressure of liquid water (kJ/kg K)
C_{pi}	specific heat at constant pressure of ice (kJ/kg K)
h_f	specific enthalpy of saturated liquid (kJ/kg)
h_g	specific enthalpy of saturated vapour (kJ/kg)
h_{fg}	specific latent enthalpy of vaporisation (kJ/kg)
h_{if}	specific latent enthalpy of fusion (kJ/kg)
$\dot{m}_{evap}$	evaporator low-pressure steam flow (kg/s)
$\dot{m}_{ice}$	rate of ice making (kg/s)
$\dot{m}$	mass flow (kg/s)
$\dot{Q}_{ice}$	coolth storage rate (kW)
TIS	thermal ice storage or store
ΔT_{sc}	degree of supercooling (°K)

Subscripts

evap	evaporator
con	condenser
gen	steam generator
sc	supercooling
spray	spray-nozzle
TIS	thermal ice storage

of 200 kPa. This steam flows through a pipeline to the jet-pump assembly shown in Fig. 2, where it enters via the primary (de Laval) nozzle, shown in Fig. 3. As the high pressure steam expands through the nozzle its velocity increases to about 1100 m/s whilst its pressure can fall to as low as 250 Pa. The effect of this is to produce a vacuum pressure within the evaporator vessel from where a low-pressure secondary flow stream is drawn and entrained by the primary flow. The ratio between the secondary and primary flow is called the entrainment ratio.

The combined secondary and primary flow is then compressed as it passes through a convergent-divergent diffuser causing its static pressure to rises to equal that in the condenser vessel. The flow then condenses within the condenser from where some of the condensate is returned to the evaporator vessel whilst the remainder is pumped under pressure to the generator. Eames and Wu [6], provide a more comprehensive description of the operation and design of jet-pumps.

Of particular interest to this paper is the operation of the evaporator, which also acts as the thermal ice storage vessel. The water vapour which is drawn from it by the jet-pump is evolved by the evaporation of liquid water within the vessel. Because there is no heat transfer through the walls of the vessel the evaporator can be assumed to be adiabatic and therefore any evaporation that takes place causes the liquid water within the vessel to cool. In order to encourage this evaporative cooling process the surface area of the liquid water is increased by the use of a spray nozzle, shown in Fig. 1. This breaks the liquid into small droplets, which enhances both heat and mass transfer. The chilled water produced is circulated via a pump through the building cooling system heat exchanger where is heated by the building cooling water.

If the jet-pump is designed so that under normal operation it produces a greater amount of cooling than the building requires then the water in the evaporator vessel can be made to freeze. Under such conditions our experiments showed that freezing takes place on the vertical surface of the evaporator vessel forming a circular ring of clear ice several centimetres thick and quickly extending over half the height of the vessel as illustrated in Fig. 1. When the solar derived heat is taken away from the steam generator both the primary and secondary flows reduce. However, building cooling can be maintained as long as ice is present within the evaporator.

In principle the same refrigerant water that flows through the spray nozzle and which is cooled in the evaporator vessel could be pumped around the building cooling system, which would provide a higher COP than the system proposed here. In practice however, the need to maintain a high vacuum on evaporator side of the system and the need to prevent air being absorbed into the refrigerant water require the low-pressure evaporator circuit to be physically as compact as possible. To achieve this it is necessary to separate building cooling water and evaporator water circuits which are thermally connected by the heat exchanger shown in Fig. 1.

3. Experimental apparatus

The test apparatus, shown in Fig. 4, consisted of four main elements, an evaporator, a condenser, a steam generator and the

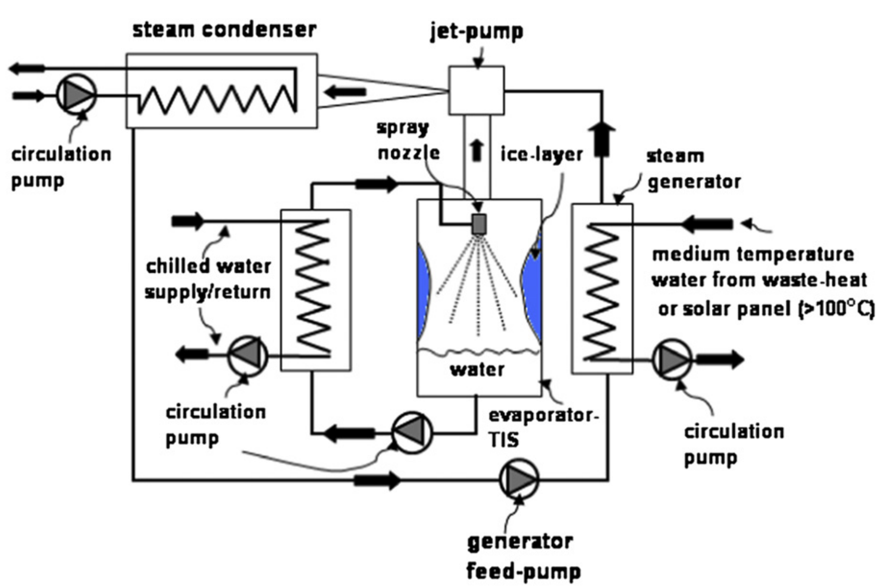

Fig. 1. Showing the proposed jet-pump – thermal ice storage system.