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Ejector and Air Cycle Refrigeration Technologies for Foods

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Abstract: Food refrigeration is an important part of the modern day food industry. It is used in all stages of the chain, from food processing, to distribution, retail and final consumption in the home. The food industry employs both chilling and freezing processes, and in these processes mechanical refrigeration technologies are invariably employed that contributes significantly to the environmental impacts of the food sector both through direct and indirect greenhouse gas emissions. To reduce these emissions, research and development worldwide is aimed at both improving the performance of conventional systems and the development of new refrigeration technologies of potentially much lower environmental impacts. This paper provides a brief review of both current state of the art technologies and emerging ejector and air cycle refrigeration technologies that have the potential to reduce the environmental impacts of refrigeration in the food industry.

Keywords: Ejector, Air cycle, COP, Food refrigeration.

Introduction

Ejector or jet pump refrigeration is a thermally driven technology that has been used for cooling applications for many years. In their present state of development they have a much lower COP than vapour compression systems but offer advantages of simplicity and no moving parts. Their greatest advantage is their capability to produce refrigeration using waste heat or solar energy as a heat source at temperatures above 80 ^{0}C.

Referring to the basic ejector refrigeration cycle and T–s diagram in Fig. 1, the system consists of two loops, the power loop and the refrigeration loop (Tassou, et al., 2010). 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 vapour generated, known as the primary fluid, flows through the ejector where it accelerates through the nozzle. The reduction in pressure that occurs induces vapour 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 portionof the liquid exiting the condenser at point 5 is then pumpedto the boiler for the completion of the power cycle. The remainderof the liquid is expanded through an expansion device and entersthe evaporator of the refrigeration loop at point 6 as a mixture ofliquid and vapour. The refrigerant evaporates in the evaporatorproducing a refrigeration effect, Qe, and the resulting vapour isthen drawn into the ejector at point 3. The refrigerant (secondaryfluid) mixes with the primary fluid in the ejector and is compressedin the diffuser section before entering the condenser at point 4. Themixed fluid condenses in the condenser and exits at point 5 for therepetition of the refrigeration cycle.

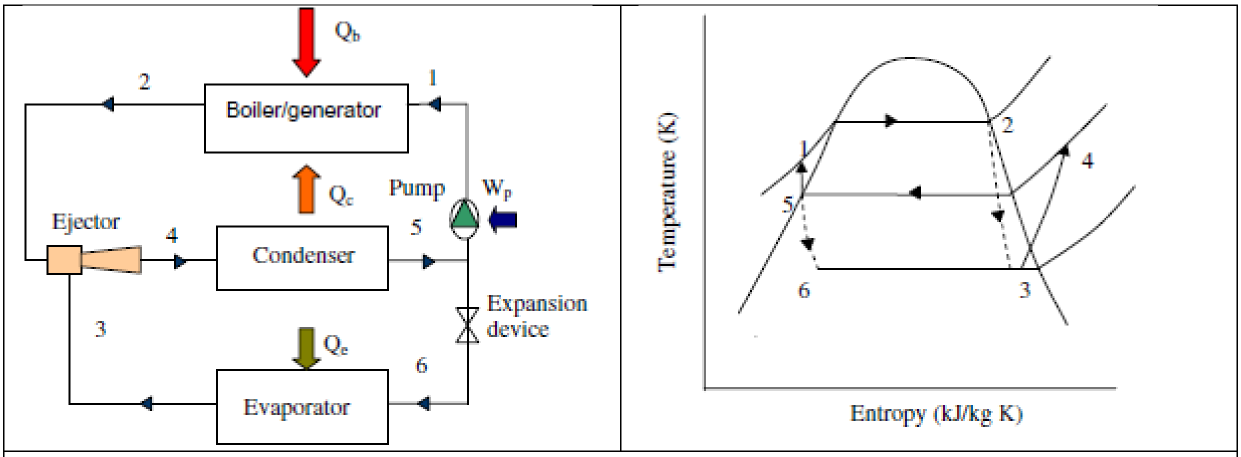

Fig. 1. Schematic and T–s diagram of ejector refrigeration system.

Air cycle systems produce low temperatures for refrigeration by subjecting the gaseous refrigerant (air) to a sequence of processes comprising compression, followed by constant pressure cooling, and then expansion to the original pressure to achieve a final temperature lower than at the start of compression. In practice the basic reversed Joule (or Brayton) cycle is modified by including regenerative heat exchange and, in some systems, multi-stage compression with intercooling as illustrated in Fig. 2 (Tassou, et al., 2010).

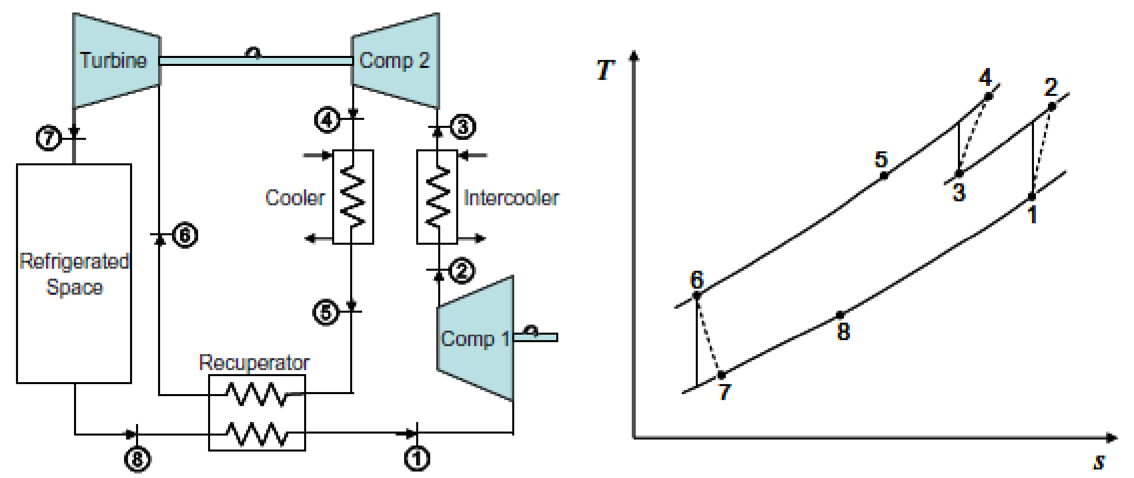

Fig. 2. Air cycle with regenerative heat exchange and two-stage compression with intercooling.

Air cycles can be classified as closed, open or semi-open/closed (Williamson, et al., 2005). Closed cycles are, by definition, sealed systems and consequently there is no direct contact between the working fluid and the product being cooled. Hence, in comparison with open and semi-open/closed cycles, an additional heat exchanger (with associated temperature difference) is required for transferring heat from the refrigeration load. Open cycles are open to the atmosphere on either the low-pressure side or the high-pressure side of the cycle and the cooled air passes directly through the refrigerated space. Semi-open/closed cycles are also open to the refrigerated space, but the air is then drawn back through the lowpressure side of the regenerator to the compressor.

State of Development

The first steam ejector refrigeration system was developedby Maurice Leblanc in 1910 and gained in popularity for air conditioning applications until the development of chlorofluorocarbon refrigerants in the 1930s and their use in the vapour compression cycle which was much more efficient than alternative thermally driven cycles. Research and development continued however and the ejector technology found applications in many engineering fields particularly in the chemical and process industries (Eames, et al., 1995, Chunnanond, el al., 2004, Sherif, et al., 1998, and Alexis, 2005).

Systems have been developed with cooling capacities ranging from a few kW to 60,000 kW but despite extensive development effort the COP of the system, which can be defined as the ratio of the refrigeration effect to the heat input to the boiler, if one neglects the pump work which is relatively small, is still relatively low, less than 0.2. Ejector refrigeration systems are not presently commercially available off the shelf but a number of companies specialise in the design and application of bespoke steam ejector systems that use water as a refrigerant for cooling applications above 0 ^{0}C (Tassou, et al., 2010).

To improve the efficiency of the simple ejector cycle more complex cycles have been investigated (Yu, et al., 2006) as well as the integration of ejectors with vapour compression and absorption systems. Significant effort has also been devoted to the development of solar driven ejector refrigeration systems (Pridasawas, 2006).

While, air cycle refrigeration is an environmentally friendly and reasonably well established, albeit under-exploited, technology. Plant and component operating characteristics are understood and issues such as condensation and icing have been addressed and solutions developed. Air cycle plants have been developed by industrial companies with refrigeration capacities ranging from 11 to 700 kW for closed systems and from 15 to 300 kW for open or semi-open/ closed systems (Kikuchi, et al., 2005, Shaw, et al, 1995). Information on coefficient of performance for air cycle refrigeration systems is sparse but most values quoted are in the range 0.4–0.7. Furthermore, the efficiency of air cycle systems is relatively unaffected under part-load conditions.

Applications in the Food Sector

Applications in the food sector will be primarily in areas where waste heat is available to drive the ejector system. Such applications can be found in food processing factories where the ejector refrigeration system can be used for product and process cooling and transport refrigeration. Other possible application is in tri-generation where the ejector refrigeration system can be used in conjunction with combined heat and power systems to provide cooling.

While, air cycle refrigeration can deliver air temperatures down to -100 ^{0}C or below, giving it a niche position in the -50 to -100 ^{0}C range, beyond the capability of vapour compression plant, and is a cost-effective alternative to the use of cryogenics for low temperature food freezing operations. Air cycles can also generate high air temperatures, typically of over 200

^{0}C, that can be used in combination with the low temperatures to integrate cooking and refrigeration processes (Tassou, et al., 2010).

Air cycle technology has been evaluated for food sector applications including rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment); cold storage, refrigerated storage cabinets, refrigerated transport (trucks, containers, rail freight); and for integrated rapid heating and cooling i.e., cook–chill–freeze or hot water/steam raising and refrigeration (Russell, et al., 2001, Spence, et al, 2005, Evans, et al., 2006).

Barriers to Uptake of the Technology

Themainbarriers touptake of ejector refrigerationtechnologyare: lower COPs, 0.2–0.3, compared to vapour compression systems and other thermally driven technologies. The COP also drops significantly at operation away from the design point, and unavailability of off the shelf systems to facilitate selection for particular applications and lack of performance data from commercial applications to provide confidence in the application of the technology.

The main barriers to uptake of air cycle technology are, unavailability of packaged equipment off the shelf for application in the food sector, insufficient experience and performance data from commercial applications to provide confidence in the application of the technology (Tassou, et al., 2010).

Key Drivers to Encourage Uptake

The main drivers to encourage uptake of the ejector refrigeration technology in the food sector are, successful demonstration of the benefits of the technology in applications where there is sufficient waste heat or in tri-generation systems, and rising energy costs that could encourage the more effective utilisation of waste heat and better thermal integration of processes in food manufacturing.

The main drivers to encourage uptake of the air cycle technology in the food sector are, rising energy costs and requirement for faster food processing to increase throughput and reduce energy consumption, more stringent regulations on the use of HFC refrigerants and other natural refrigerant alternatives(Tassou, et al., 2010).

Conclusion

To increase the attractiveness and application of ejector refrigeration systems research and development is required to, increase the efficiency of steady flow ejectors particularly atoperation away from the design point, develop alternative ejector types, such as rotodynamic ejectors (Hong, et al., 2004) that offer potential for higher efficiencies, develop ejectors that can operate with other natural refrigerants apart from water, such as CO_2 and hydrocarbons, to extend therange of applications to below 0^0C, research into the optimisation of cycles and the integration of ejectors with conventional vapour compression and absorption systems.

To increase the attractiveness of air cycle systems, research and development is required to, successfully demonstrate the benefits of the technology in specific promising applications, such as: combined refrigeration and cooking/heating and transport refrigeration, increase the efficiency and availability of small turbo-machines, improve the effectiveness and reduce costs of compact heat exchangers, and develop component sizing, integration and control strategies for specific applications to increase system efficiency at reasonable cost.

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