INTERNATIONAL JOURNAL OF REFRIGERATION 34 (2011) 1699–1706

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Theoretical study and design of a low-grade heat-driven pilot ejector refrigeration machine operating with butane and isobutane and intended for cooling of gas transported in a gas-main pipeline☆

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ARTICLE INFO

Article history:
Received 2 February 2010
Received in revised form
6 January 2011
Accepted 19 January 2011
Available online 27 January 2011

Keywords:
Ejector
System
Butane
Isobutane
Gas turbine
Gas pipeline

ABSTRACT

This paper describes the construction and performance of a novel combined system intended for natural gas transportation and power production, and for cooling of gas transported in a gas-main pipeline. The proposed system includes a gas turbine compressor, a combined electrogenerating plant and an ejector refrigeration unit operating with a hydrocarbon refrigerant. The combined electrogenerating plant consists of a high-temperature steam–power cycle and a low-temperature hydrocarbon vapor power cycle, which together comprise a binary vapor system. The combined system is designed for the highest possible effectiveness of power generation and could find wide application in gas-transmission systems of gas-main pipelines. Application of the proposed system would enable year-round power generation and provide cooling of natural gas during periods of high ambient temperature operation. This paper presents the main results of a theoretical study and design performance specifications of a low-grade heat-driven pilot ejector refrigeration machine operating with butane and isobutane.

Etude théorique et conception d'un système frigorifique pilote à éjecteur à récupération de chaleur á butane et á isobutane destiné à refroidir le gaz acheminé dans un conduit

Mots clés : Éjecteur ; Systéme ; Butane ; Isobutane ; Turbine à gaz – gazoduc

☆ This paper is an updated version of the paper No.07 presented at the International Seminar on ejector/jet-pump technology and application, September 7-9, 2009, Louvain-la-Neuve, Belgium.

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doi:10.1016/j.ijrefrig.2011.01.016

Nomenclature

A	area (mm^2)
c	specific heat of liquid (kJ kg^{-1} K^{-1})
COP	coefficient of performance
ERM	ejector refrigeration machine
h	specific enthalpy (kJ kg^{-1})
L	length (m)
M	molecular weight (kg $kmol^{-1}$)
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
Q	heat flow (kW)
q	specific heat of evaporation (kJ kg^{-1})
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C or K)
v	specific volume (m^3 kg^{-1})
$\dot{W}$	power (kW)

Greek letters

α	ejector area ratio
η	coefficient of efficiency
λ	latent heat of vaporization (kJ kg^{-1})
ω	entrainment ratio

Subscripts

c	condenser
cr	critical
e	evaporator
ej	ejector
g	generator
mech	mechanical
nb	normal boiling
p	primary
pump	feed pump
s	secondary
t	throat
therm	thermal
1, 2, 3	cross-sections of the ejector (Fig. 3, Eq. (2))
1, 2, 3…9	cycle states in the Fig. 2, Eq. (4)

1. Introduction

The ejector refrigeration cycle offers a low capital cost solution for utilizing low-grade heat to provide cooling for buildings and for process refrigeration. Since waste heat is widely available and its supply cost is negligible in many cases, cooling costs can be reduced below those of conventional electrically powered vapor compression systems, making this method very attractive (Sun and Eames, 1995; Chunnanond and Aphornratana, 2004; Petrenko et al., 2005b). Recently, several high efficiency ejector refrigeration machines (ERMs), operating with refrigerants R141b and R245fa, were developed and coefficients of performance (COP) in the range of 0.5–0.7 were obtained under practical operating conditions. These results are very encouraging for air-conditioning and cooling applications because these COPs are similar to those for absorption cycle machines (Huang et al., 1999; Eames et al., 2007).

One of the prospective directions towards energy savings and environmental protection is the application of systems that utilize waste energy in gas-transmission systems. Gas turbine engines, which have found wide application at gas-transfer stations as driving motors for gas turbocompressors, discharge exhaust gases with temperatures up to 400–550 °C into the environment. This vast and presently unused waste heat could be effectively utilized by innovative combined systems composed of electrogenerating plants and ejector cooling units (Prytula et al., 2007; Petrenko and Volovyk, 2008).

In the present paper, construction of this novel type of combined system is proposed. The system is intended for simultaneous natural gas transportation and power production, and for the cooling of gas transported in gas-main pipelines. Utilization of the proposed combined system recovers approximately 75–85% of the exhaust heat.

The main objective of this research is the theoretical study and design of low-grade heat-driven pilot ERMs, operating with butane and isobutane and intended for cooling of natural gas transported in gas-main pipelines.

2. Design of a combined system

Fig. 1 shows a schematic diagram of a combined system intended for simultaneous natural gas transportation and power production, and for cooling of gas transported in gas-

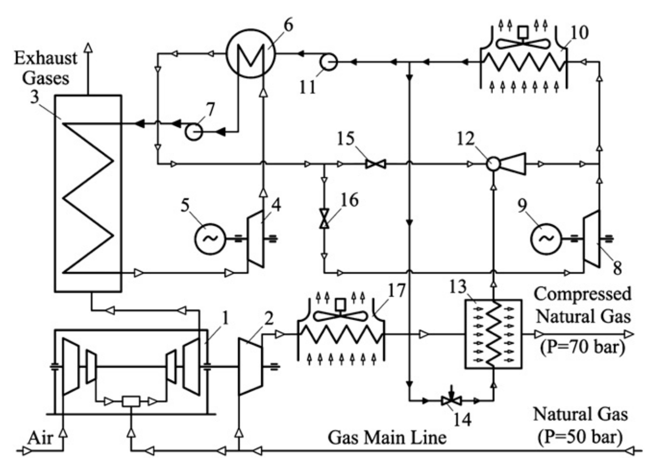

Fig. 1 – Diagram of combined system: 1 – gas turbine engine; 2 – gas turbocompressor; 3 – waste heat recovery boiler; 4 – steam turbine; 5, 9 – electric generators; 6 – condenser – vapor generator; 7, 11 – feed pumps; 8 – hydrocarbon turbine; 10 – air-cooled condenser; 12 – ejector; 13 – evaporator - gas cooler; 14 – expansion valve; 15, 16 – shutoff valves; 17 – gas cooler.