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Performance of the one-stage Joule–Thomson cryocooler fed with a nitrogen–hydrocarbon mixture and built from mass-produced components made for the refrigeration industry

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ABSTRACT

This paper describes the theoretical performance and working parameters of a Joule–Thomson (J-T) cryocooler that is supplied with a nitrogen–hydrocarbon mixture and works in a closed cycle. Nowadays, they are the subject of intensive research in different laboratories around the world, especially in Asia and the USA. The industrial application of this type of cooler is significantly limited by the high values of working pressure for pure nitrogen. Supplying the system with a mixture of nitrogen and hydrocarbons makes it possible to reduce the level of the working pressure down to that which is achieved by commercially available compressors produced for the refrigeration industry. A theoretical analysis of the performance of the cooler is presented, along with the experimental results for different mixtures. The described cooler is characterized by high reliability, simple construction in the low-temperature section, and relatively low manufacturing costs. The system produces about 10 W of cooling power at an approximate temperature of 90 K. The cooling power can be used to cool down high-temperature superconductor magnets, in nanotechnology, for cryomedical applications, and to liquefy small amounts of nitrogen, argon, oxygen, or methane.

Performance d'un cryorefroidisseur Joule-Thomson monoétagé fonctionnant avec un mélange azote-hydrocarbure et construit à partir de composants produits à grande échelle pour l'industrie du froid

Mots clés : Cryorefroidisseur Joule-Thomson ; Mélanges de gaz ; Composants frigorifiques ; Liquéfacteur d'azote

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Nomenclature

Acronyms
COP Coefficient of Performance
LNG Liquefied Natural Gas
MLI Multi Layer Insulation
PSA Pressure Swing Adsorption

Symbols
$\%_{Carnot}$ Efficiency compared to the Carnot efficiency [%]
Δh_T Isothermal mass enthalpy difference [kJ · kg^{-1}]
$\dot{P}$ Compressor power consumption [W]
$\dot{Q}$ Cooling power [W]
$\dot{v}$ Volume flow rate [m^3 · kg^{-1}]
η Efficiency [-]
ρ Density [kg · m^{-3}]
w Specific work [kJ · kg^{-1}]
p Pressure [kPa]
T Temperature [K]

Subscripts
c Carnot
com Compression
gross Gross
HX Heat exchanger
i Ideal
ins Insulation
l Low
min Mminimum
net Net
o Ambient
v Volumetric

1. Introduction

In recent years, there have been significant developments in high temperature superconductivity and LNG technology. Low temperatures are commonly used in medicine, agriculture, food processing, and industry. Therefore, the demand for reliable and cheap coolers which produce relatively high cooling power in temperatures around 90 K has risen. Moreover, the application of liquefied gases, e.g., liquid nitrogen, oxygen, and methane, has gained importance in some industrial sectors as well.

Commercially available cryogenic coolers have different cooling capacities and operating temperature limits, depending on application. Low-capacity coolers, such as micro Joule–Thomson (J-T) coolers, are mainly used to cool down infrared detectors and also in laboratories where the capacity is lower than 1 W (Derking et al., 2012; Maytal, 2015; Tzabar and Kaplansky, 2014). Higher cooling capacities can be obtained with the use of a cryostat that is periodically filled with liquid nitrogen. However, this is not recommended in prolonged applications. On the other hand, cryogenic gas coolers, e.g., the Gifford-McMahon or pulse-tube, are relatively expensive and their usage is economically justified only if applied to cool down objects at temperatures near the boiling point of helium (4.2 K) (Hu et al., 2014; Huang and Chang, 1995; Yamada, 2014), e.g., in superconductivity or superfluidity studies.

Based on the abovementioned data, there appears to be a specific gap in the cooler market. On the one hand, there are relatively cheap cryocoolers which are able to reach mW of cooling power and temperatures around 77 K (the boiling point of liquid nitrogen). On the other hand, coolers with capacities of twelve to several dozen Watts are very expensive. The production of a simple and reliable one-stage cooler which works in a closed cycle and is able to produce over a dozen Watt in about 90 K could fill the gap in the market and expand the range of cryocoolers currently in use. Such coolers may be used in small liquefiers of nitrogen, oxygen, and methane (including LNG recondensation in storage tanks), in cryomedical devices, or in scientific research. Moreover, they could also be an interesting solution for nanotechnology, where small amounts of well-defined liquefied substances are crucial (Malecha and Malecha, 2014). However, the criterion of low production cost can only be met if the cooler is characterized by simple construction and built with cheap and easily accessible components which have been mass-produced for the refrigeration industry. Using the J-T cooler fed with a gas mixture makes this possible. That is why this paper is based on determining the appropriate gas mixture composition to meet the abovementioned requirements. Moreover, the theoretical analysis of the performance of the cooler is applied to the chosen mixtures and then verified experimentally on the test stand. Based on the analysis, the optimal mixture is chosen, and used in further studies focused on nitrogen liquefaction.

1.1. *A description of the Joule–Thomson cryocoolers*

One-stage Joule–Thomson cryocoolers and liquefiers are the simplest pieces of equipment used to liquefy gas or produce cooling power at the boiling temperature of liquid nitrogen, i.e., 77 K. The J-T cryocooler is characterized by a lack of moving parts in low temperature, which makes miniaturization (even up to a few centimeters) possible. Due to the high working pressure which is needed at the inlet of the recuperative heat exchanger and low thermodynamic efficiency, J-T coolers are usually manufactured in miniature versions and used in open systems, i.e., supplied with gas from a cylinder (Fig. 1). Compressed gas from the cylinder is supplied to the recuperative heat exchanger where it is cooled down – processes 2–3 in Fig. 1a. Next, the gas is throttled and partially liquefied (3–4). The liquefied gas can then evaporate inside the evaporator and generate cooling power (4–5), or can be removed from the device. The cold gas is then transferred to the recuperative heat exchanger where it is heated (5-1′). The gas is then released into the surroundings. As a consequence of the imperfections of heat transfer in the recuperative heat exchanger, the temperature at point 1′ is a few K lower than at point 1.

The maximum working pressure is bound only by material limitations and compressor capacities. However, as the inversion pressure of pure nitrogen is around 36 MPa, if the pressure were to increase, then the temperature of the gas would rise during throttling, which should also be considered. On the other hand, research has established that the minimum working