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Research paper

Development and performance test of a miniature movable mixed-refrigerant liquid nitrogen generator

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ABSTRACT

In order to cover long-term but small quantity liquid nitrogen requirements of laboratory or field users, a miniature movable mixed-refrigerant liquid nitrogen generator (MRLN) was developed and tested here, based on a precooled mixed-refrigerant J-T (MRJT) refrigerator. With the full air-cooled, skid-mounted structure, this MRLN was built utilizing off-the-shelf refrigeration components like commercial single-stage oil-lubricated compressors to reduce construction cost greatly. Bottled pure N_2, pressure swing adsorption (PSA) unit and mini cryogenic rectification column could be employed to supply N_2 in different operation modes respectively. In pure N_2 mode, N_2 was directly liquefied by the MRJT refrigerator. With feed N_2 at 0.8 MPa, the specific power consumption (*SPC*) was 1.79 kWh L^{-1}, and figure of merit (*FOM*) was 6.27%. The estimated *SPC* in PSA mode was 2.68 kWh L^{-1}. For column mode, the *SPC* was 4.59 kWh L^{-1}, with *FOM* of 3.38%. A closed N_2 cycle could convey cooling capacity between flammable refrigerant and air. This MRLN could be a convenient and low-costing choice for some liquid nitrogen users.

1. Introduction

Liquid nitrogen (LN_2) is extensively used in cryogenic engineering. However, the procurement and preservation of LN_2 could be relative inconvenient in field environment that is far away from normal LN_2 supply facilities. It might also be uneconomical for laboratories to buy LN_2 with long-term small quantity requirement. Miniature LN_2 generators could be satisfying solutions under above conditions.

In miniature LN_2 generators, different cooling sources could be employed for gas liquefaction, such as helium regenerative cryocoolers (Stirling, G-M, etc.), feed gas expansion processes, and mixed-refrigerant J-T (MRJT) refrigerators. Except for bottled pure N_2, feed N_2 could be separated from air by cryogenic air separation column, pressure swing adsorption (PSA) unit or membrane separation unit [1,2]. PSA and membrane separation units are satisfying for miniature systems for simple configurations and no cryogenic component.

Many commercial miniature LN_2 generators are the combination of PSA air separation units [3–7] and Stirling [3,4] or G-M [5–7] cryocoolers. N_2 is separated from compressed air by PSA units at ambient temperature and liquefied by the cold head of cryocoolers [3–7]. These LN_2 generators could be very compact due to the small size of cryocoolers. Their startup time is also short. For example, the G-M cryocooler for [6] could reach 20 K in 35 min with no load [8]. However, the construction cost of helium regenerative cryocoolers might be higher than the MRJT refrigerators with similar cooling capacities near liquid nitrogen temperature [9].

Feed gas expansion processes are mainly combined with air separation columns in large cryogenic air separation plants, which are also the basic method for industrial LN_2 production [2]. However, miniature gas expansion type LN_2 generators with LN_2 output less than 10 L h^{-1} are not prevalently manufactured. The gas expansion type miniature LN_2 generators in [10–12] are based on modified Claude or Kapitza cycles with mini turbine expanders, whose configurations are simple, free of external refrigerators. A cryogenic air separation column could be directly installed after the expansion liquefier [11]. However, the specific power consumptions (*SPC*) of these LN_2 generators are higher than those in G-M + PSA LN_2 generators and large scale air separation plants.

In the temperature zone of low pressure air and N_2 liquefaction (such as 100.4 K of N_2 at 0.8 MPa, which is a typical operating pressure for small commercial air compressors), MRJT refrigerators have advantages such as satisfying efficiency, favorable volumetric cooling capacity, no cryogenic moving component and low construction cost [13–15]. Similar with the MRC processes in natural gas liquefaction

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Nomenclature

BOG	boil-off gas
E	exergy flow (kW)
e	specific exergy ($kJ\,kg^{-1}$)
FOM	figure of merit ($kW\,kW^{-1}$, %)
g_v	volumetric flow rate ($m^3\,h^{-1}$, $L\,h^{-1}$)
HC	hydrocarbon
LN_2	liquid nitrogen
m	mass flow rate ($g\,s^{-1}$)
MRJT	mixed-refrigerant Joule-Thomson (cycle)
MRLN	mixed-refrigerant liquid nitrogen generator
p	pressure (MPa)
p_h	compressor discharge pressure (MPa)
p_l	compressor suction pressure (MPa)
RO_2	oxygen-enriched air
SPC	specific power consumption ($kWh\,L^{-1}$)
T	temperature (K)
T_0	ambient temperature (K)
W	power consumption (W, kW)

Greek letters

η	exergy efficiency ($kW\,kW^{-1}$, %)

Subscripts

AC	after cooler
air	open air cycle (feed air)
AJT	after throttling
BJT	before throttling
c	cooling capacity
CP	compressor
HX1	precooling multi-flow heat exchanger
HX2	middle (recuperative) multi-flow heat exchanger
HX3	cold (recuperative) multi-flow heat exchanger
HX4	air liquefaction multi-flow heat exchanger
h	high pressure (warm) stream
in	inlet status
JT	JT element
l	low pressure (cold) stream
main	main cycle
N2	open nitrogen cycle, feed nitrogen
N2C	closed nitrogen cycle
out	outlet status
prec	precooling cycle
RO2	oxygen enriched air
sep	separation
0	ambient

industry, N_2 is liquefied in the recuperative heat exchanger by the low pressure cold refrigerant stream. Thermodynamic analysis of several mixed-refrigerant type nitrogen liquefaction processes are conducted in [16,17], focusing on high pressure (2.0–4.0 MPa) and low pressure (near 0.8 MPa) N_2 sources, respectively. It is indicated that MRJT refrigeration processes could be cooling sources for N_2 liquefaction. However, the prototype construction and experimental investigation of mixed-refrigerant LN_2 generators (MRLN) are rarely reported, especially for low pressure N_2 liquefaction. Some MRLN prototypes are developed with two-stage mixed-refrigerant compressors [18] and high pressure N_2 sources (≥ 2.0 MPa) [18,19]. Although the *SPC* could be relatively low, the system construction cost might be higher. Membrane units are used in [18,19] instead of cryogenic air separation columns. Little [20] developed a low-costing commercial miniature MRLN based on an air-cooled auto-cascade MRJT refrigerator driven by an oil-lubricated compressor. Feed N_2 is supplied by a PSA unit and a small air

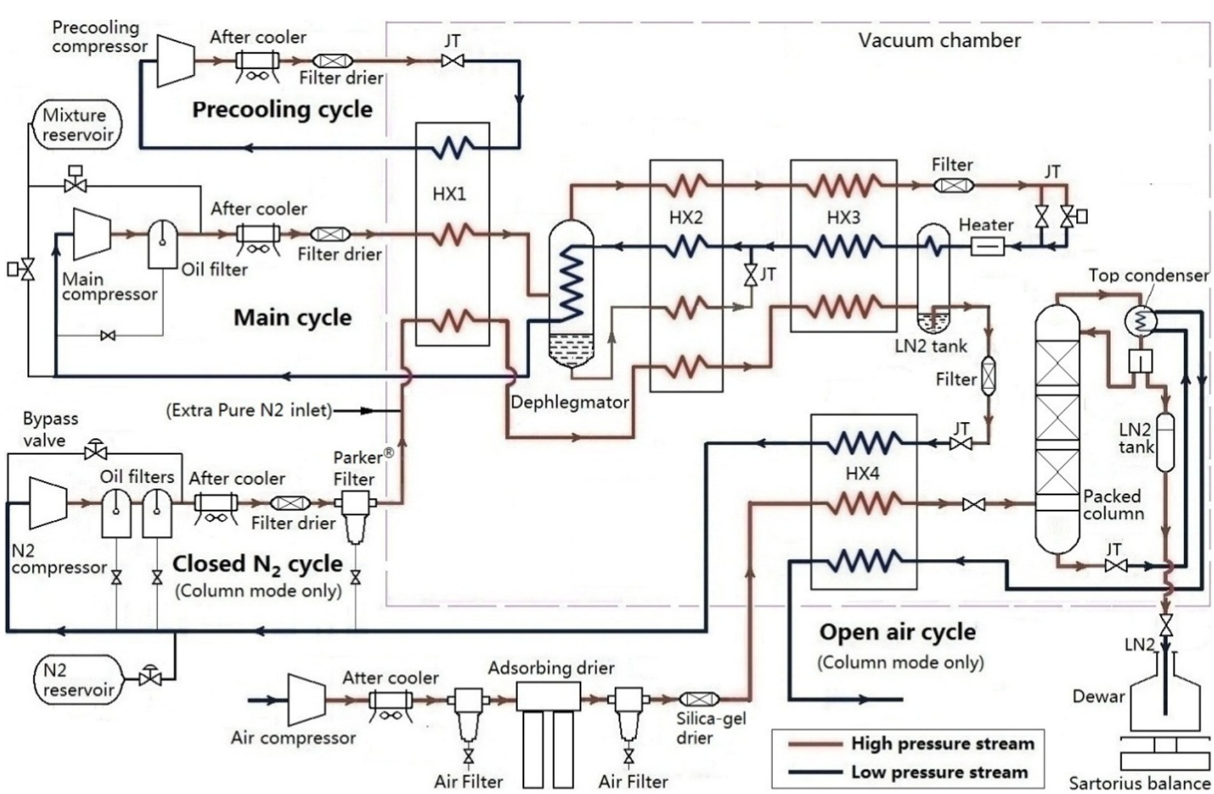

Fig. 1. Diagram of MRLN prototype (whole system, using air separation column).