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Thermodynamic analysis of regenerated air-cycle refrigeration in high and low pressure configuration

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ARTICLE INFO

Article history:
Received 26 July 2013
Received in revised form
9 October 2013
Accepted 13 November 2013
Available online 25 November 2013

Keywords:
Air cycle
Regenerator
Low temperature refrigeration

ABSTRACT

A thermodynamic analysis is performed on open, regenerated, inverse air-cycles, focussing on low temperature refrigeration, in order to provide general optimization criteria, support for a rational configuration choice and potential performance improvement for this specific application. The effect of high regenerator effectiveness (0.95) is explored, showing that it may double the air cycle COP in the case at hand. Low and high pressure configurations (i.e. featuring only one heat exchanger on the cold or hot cycle side) are compared. High pressure configuration, normally preferred in the field of low temperature refrigeration, has a lower efficiency, but the gap reduces as regenerator effectiveness increases. Avoidance of a cold heat exchanger eliminates frosting problems and power input for the circulation fan, so that the small COP decrease suffered by the high pressure cycle can easily be compensated for and eventually yield higher average plant efficiency. The feasibility of such a highly effective regenerator, already reported in the literature, is demonstrated using classic Kays and London (1964) data.

Analyse thermodynamique de froid à cycle d'air régénéré en configurations de haute et basse pressions

Mots clés : Cycle d'air ; Régénérateur ; Froid à basse température

1. Introduction

The use of air compression/expansion to obtain a cooling effect was among the first methods of mechanical refrigeration (Gladstone, 1998). The advantages of air as a refrigerant are evident: it is free, absolutely safe for environment and operators and, above all, ubiquitously available. This allows continuous charge/discharge to the ambient, a unique feature among refrigerant fluids, eliminating the need for a sealed circuit.

The circuit can be open towards the ambient (a hot air outlet substitutes for the hot side heat exchanger) or towards the refrigerated space (the cold side heat exchanger is eliminated). In both cases, irreversibilities related to heat transfer and flow friction, as well as cost, weight and volume, are

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0140-7007/$ – see front matter
http://dx.doi.org/10.1016/j.ijrefrig.2013.11.017

Nomenclature

A	Heat exchange surface (m^2)
B	Heat exchanger height (m)
COP	Coefficient Of Performance
c_p	Specific heat at constant pressure (J kg^{-1} K^{-1})
h	Convective heat transfer coefficient (W m^{-2} K^{-1})
L	Heat exchanger length (m)
$\dot{m}$	Mass flow rate (kg s^{-1})
n_p	Number of heat exchanger plates
p	Pressure (Pa)
$\dot{Q}$	Thermal power (W)
R	Ideal gas universal constant (J kg^{-1} K^{-1})
s	Specific entropy (J kg^{-1} K^{-1})
T	Temperature (K)
V	Heat exchanger volume (m^3)
$\dot{W}$	Mechanical power (W)
α	Heat surface density (m^{-1})
β	Compression ratio
ε	Kays' thermal effectiveness
η	Efficiency
θ	Dimensionless cooling load
λ	Iso-entropic exponent

Subscripts

1	first stage
2	second stage
c	compression
C	Carnot
e	expansion
g	global exchange surface
H	high
II	2^{nd} law of Thermodynamics
L	low
min	minimum
opt	optimal
p	polytropic
r	regenerator
W	heat exchanger surface

avoided. In the second case, elimination of the evaporator has further advantages in terms of frost avoidance on cold surfaces. If the cold air is introduced at a suitable speed in the cold space, the electric fan fitted on the evaporator can be eliminated as well.

For the moment, except for air conditioning systems on airplanes, examples of commercially available air cycle refrigeration systems are rare. In the air conditioning field, a system, patented by Kinsell et al. (1977), is used at the prototype stage on German high speed trains (Liebherr, 2010). Exhaust air from the cool space is used as the refrigerant fluid, allowing recovery of energy without an additional heat exchanger. The avoidance of fluid leakage problems increases reliability and, hence, attractiveness of the air cycle for air conditioning on mobile applications. Another system is proposed for Chinese high speed trains (Zhang et al., 2011).

Among stationary systems, to the best of our knowledge, the only ready-to-market one is the "Pascal Air" manufactured in Japan by Mayekawa (Boone and Machida, 2011). A similar system is also foreseen by Mitsubishi (Kikuchi et al., 2005). These systems feature a regenerated, semi-open, high-pressure cycle with a single stage compression and turbine mounted on magnetic bearings (Nakazeki et al., 2009). In the past, Air Products manufactured the "ColdBlast" open-cycle freezer (Shaw et al., 1995) which evolved in the "CCAR" closed-cycle system (Pelsoci, 2001), featuring maximum pressure as high as 63 bar and minimum cold space temperature as low as −100 °C. Another system that reached a pre-commercial stage of development is "AIRS50", developed by Kajima Inc. and later by Earthship Ltd., featuring a staged compression (Gigiel et al., 2006).

From a thermodynamic point of view, the use of a gaseous fluid throughout the cycle changes the reference cycle from Carnot rectangular shape to the inclined shape of the Joule cycle. If the refrigeration is performed between constant temperature heat sources, like ambient air or a steady state cold store, the constant-temperature heat exchange along a phase change process obviously minimizes the temperature difference between the fluids.

However, the constant temperature heat rejection sought by the Carnot cycle is not reached even in vapour-compression refrigerators, the fluid at compressor exit being significantly superheated.

On the cold side, a constant temperature evaporator is desirable as long as the cold space remains at constant (and small) temperature difference from the refrigerating fluid. In the opposite case of food freezing, a counter-flow heat exchange between the cooling medium and the food would be preferable and a large temperature range covered by the air along the freezing path would actually reduce heat exchange irreversibility. In general, all applications with finite heat capacity sources will benefit from a sensible, rather than latent heat exchange and the thermodynamic gap with Carnot cycle can be partially compensated for by reduced external irreversibility.

Another intrinsic thermodynamic feature of the Joule cycle is expansion work recovery, while practical vapour compression refrigerators dissipate this (normally small) work on a throttling valve, to avoid the difficulty of a two-phase expansion. This can be a key difference when a very low temperature is required.

It is true that air cycle plants feature much higher fluid flow rates, sensible heat storage capability being one order of magnitude smaller than latent heat storage. However, given the moderate compression/expansion ratio, dynamic compressors and expanders may easily deal with high flow rate. High rotation speeds are easily managed through electronically controlled electric motors and magnetic bearings, ensuring low friction, reduced maintenance and oil-free operation.

Indeed, the volume of refrigeration equipments is mainly dictated by the heat exchangers. Vapour compression systems may require a small heat exchange area on the condensing/evaporating side, but nonetheless need a large surface on the air side. The air cycle being open, either on the hot or cold side, eliminates a heat exchanger. The remaining