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Performance analysis of a feasible air-cycle refrigeration system for road transport

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Abstract

The performance of an air-cycle refrigeration unit for road transport, which had been previously reported, was analysed in detail and compared with the original design model and an equivalent Thermo King SL200 vapour-cycle refrigeration unit. Poor heat exchanger performance was found to be the major contributor to low coefficient of performance values. Using state-of-the-art, but achievable performance levels for turbomachinery and heat exchangers, the performance of an optimised air-cycle refrigeration unit for the same application was predicted. The power requirement of the optimised air-cycle unit was 7% greater than the equivalent vapour-cycle unit at full-load operation. However, at part-load operation the air-cycle unit was estimated to absorb 35% less power than the vapour-cycle unit. The analysis demonstrated that the air-cycle system could potentially match the overall fuel consumption of the vapour-cycle transport refrigeration unit, while delivering the benefit of a completely refrigerant free system.

Keywords: Refrigerated transport; Air-cycle system; Research; Thermodynamic cycle; Air; Performance; COP

Analyse de la performance d'un système frigorifique à cycle à air utilisé dans le transport routier

Mots clés: Transport frigorifique ; Refroidisseur d'air ; Recherche ; Cycle thermodynamique ; Air ; Performance ; COP

1. Introduction

The concept of air-cycle refrigeration was identified in the early 1800s and the first commercial air-cycle machine appears to have been in service in 1844. A succinct historical account of developments in the field of air-cycle refrigeration is provided by Bhatti [1]. The reciprocating compression and expansion machinery used for early air-cycle machines rendered the systems inefficient and they were replaced by CO_2 vapour compression systems prior to the development of chlorofluorocarbon refrigerants. However, awareness of the environmental risks associated with using HCFC and HFC refrigerant fluids has spurred interest in alterative, natural refrigerant fluids that can deliver safe and

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Nomenclature/Abbreviations

COP	coefficient of performance
CAU	cold air unit
QUB	Queen's University Belfast
LYIT	Letterkenny Institute of Technology

sustainable refrigeration in the future. Today's highly efficient turbomachinery, which was not available to early air-cycle systems, has enhanced the performance of the air-cycle.

A previous paper by Spence et al. [2] has reported the design, construction and testing of an air-cycle refrigeration unit for road transport. The programme was supported by Enterprise Ireland and Thermo King (Ireland). The unit constructed was a demonstrator plant that was directly comparable to Thermo King's SL200 trailer refrigeration unit. The demonstrator incorporated commercially available components that were not optimised for the air-cycle system and consequently the system would not be capable of achieving the optimum performance. Testing of the demonstrator unit on Thermo King's calorimeter test facility confirmed that the original objective had been met, which was to demonstrate that an air-cycle system could fit within the existing restrictive physical envelope of the SL200 unit and develop an equivalent level of cooling power to the existing vapour-cycle unit. The measured performance of the air-cycle demonstrator is summarised in Table 1. For comparison; the standard SL200 vapour-cycle unit delivered 7.2 kW of cooling duty at −20 °C and 12 kW at 0 °C. As previously reported, the fuel consumption of the air-cycle demonstrator was much greater than that of the SL200 vapour-cycle unit. At full load operation, the air-cycle fuel consumption was over three times greater than the vapour-cycle unit, although at part load operation the fuel consumption penalty reduced from over 200% to around 80%.

Since the air-cycle demonstrator had been constructed using modified commercially available turbomachinery and compromised heat exchanger configurations, achieving good energy efficiency was never an expectation. This paper reports detailed measurements taken throughout the air-cycle demonstrator system and identifies the potential performance improvements necessary for the air-cycle system to compete on energy efficiency terms with the standard vapour-cycle unit.

2. Air-cycle demonstrator plant

Instrumentation was attached to the air-cycle demonstrator plant to measure temperature and pressure at each step around the cycle. Fig. 1 shows the two-stage compression open air-cycle system used for the demonstrator plant, which is referred to as the 'boot-strap' configuration. The diagram indicates the location of the measurement stations, each of which is numbered. Table 2 reports the average values of temperature and pressure measured at each of the three operating conditions of interest. Unfortunately an instrumentation problem during testing meant that the pressure at station 6, the aftercooler outlet, was not measured correctly.

The air-cycle demonstrator plant did not represent an ideal configuration for measuring turbomachinery efficiency, mainly because of heat transfer effects and temperature gradients in ducts. Prior to construction of the demonstrator plant, the turbomachinery components had been tested in isolation to determine their performance characteristics. Consequently, while efficiencies for turbomachinery components could be calculated directly from the measurements in Table 2, the measured pressure ratio and speed were used to determine the turbine and compressor efficiencies from the previously obtained performance maps. The mass flow rate of air through the system was also determined in this way, since it had not been measured directly on the demonstrator plant. A thermodynamic model was developed based on the measured conditions in the demonstrator plant and the known performance characteristics of the various components. The model was used to check parameters such as the work balance between the CAU turbine and compressor, and to calculate the power input to the primary compressor and power dissipated through bearing friction in the CAU. Table 3 reports the component performances at each operating condition, which were determined through the use of both the model and the experimental measurements. Due to the problem with the

Table 1
Measured performance for the air-cycle demonstrator plant

	Full-load, −20 °C	Part-load, −20 °C	Full-load, 0 °C
Cooling capacity (W)	7800	3400	9500
Ambient temperature (°C)	29.3	29.9	30.6
Trailer temperature (°C)	−20.0	−20.0	0.0
Discharge air temperature (°C)	−46.4	−35.8	−29.4
Engine speed (rpm)	2210	1760	2210