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Control strategy for aircraft vapor compression system operation

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ABSTRACT

Future, high-performance military aircraft will likely use vapor compression systems to manage the temperatures of multiple loads which are time-varying, dissimilar, and have high-turndown ratios. Experiments were performed using a scaled vapor compression system over a hypothetical flight profile to compare the temperature control performance and energy consumption of a superheat and capacity control strategy (Method A) against those of an alternate cycle-based strategy (Method B). Method B modulated the compressor speed to control the saturated suction temperature (SST) and modulated the expansion valves to directly control the evaporator heat load outlet temperature. The vapor compression system used two evaporators with dynamic and dissimilar heat loads. Method B offered better temperature control performance for the profile examined. The coefficient of performance (COP) of Method B was slightly greater than that of Method A. However if the overcooling produced by Method A was penalized, the useful COP of Method B would be meaningfully higher. Lastly, Method B did not require back pressure control valves. The use of fewer components is important for aircraft weight and reliability concerns.

Stratégie de régulation pour le fonctionnement d'un système à compression de vapeur pour avion

Mots clés : Avion ; Gestion thermique ; Système à compression de vapeur ; Régulation

1. Introduction

The thermal management of military and commercial aircraft has traditionally relied on air cycle systems to provide sufficient cooling of the cabin and cockpit for the crew and passengers, as well as for cooling other loads such as avionics. However, advanced, high-performance military aircraft have thermal management challenges far beyond the requirements of crew and passenger comfort alone. One thermal management challenge, for example, is the use of stealth technologies. Stealth aircraft designs seek to minimize the radar cross

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Nomenclature

ASH	Apparent superheat [°C]
COP	Coefficient of Performance
BPCV	Back pressure control valve
Cp	Constant pressure specific heat (J $kg^{-1}K^{-1}$)
Cv	Constant volume specific heat (J $kg^{-1}K^{-1}$)
dT	Driving temperature difference [°C]
EXV	Electronic expansion valve
h	Specific enthalpy (J kg^{-1})
INVENT	Integrated vehicle energy technology
LQI	Liquid injection
$\dot{m}$	Mass flow rate (kg s^{-1})
$\dot{Q}$	Heat transfer rate (J s^{-1})
Q	Heat transfer (MJ)
P	Pressure (Pa)
PID	Proportional integral differential
REFPROP	Reference fluid thermodynamic and transport properties software
SDP	Saturated discharge pressure [MPa]
SDT	Saturated discharge temperature [°C]
SSP	Saturated suction pressure [MPa]
SST	Saturated suction temperature [°C]
T	Temperature (°C)
ΔT	Absolute value of heat load oil temperature change across the evaporator (°C)
VCS	Vapor compression system
VCSRF	Vapor compression system research facility
$\dot{W}$	Compressor power (J s^{-1})

Subscripts

comp	Compressor
e	Evaporator
lloads	LiquidLoads
low	Coldest evaporator heat load oil set point
o	Heat load oil
4	Panel 4
5	Panel 5

Greek symbols

δ	Ratio of constant pressure specific heat to constant volume specific heat

section, which requires special treatment of any external openings. In addition, composite radar-absorbing skins have a relatively low thermal conductivity (Grant, 2010). The low effective thermal conductivity of the composite coating system essentially eliminates exterior cooling by the ambient. Future aircraft may also carry directed energy weapons that could produce waste thermal energy at a rate of 1 MW or more during operation. These weapons will present yet another daunting challenge to the thermal management system.

Another requirement for future advanced aircraft is the need for precise temperature control of multiple dissimilar loads that vary widely and rapidly. Furthermore, these loads can demand different operating temperatures. For example, the cabin air system can require 10 °C, the avionics 25 °C, the radar 20 °C, and the directed energy weapon at yet another temperature. The design challenges include accurately managing the temperature while minimizing power usage, size, and weight. Aircraft applications also have sink temperatures which vary widely in a short period. For example, the ambient temperature may be 40 °C on the ground and −20 °C at altitude. Military aircraft need to make this transition in minutes. With regard to high-performance aircraft, vapor compression system (VCS) architectures have been shown to offer higher coefficient of performance (COP) values and advantages in weight, cost, and volume relative to those of traditional air cycle systems (Iden, 2012; Engelking and Kruse, 1996; Warwick, 2012). However, the few existing airborne VCS primarily operate in an essentially steady-state manner.

One challenge for the design of advanced military aircraft VCS controls is accommodating highly transient loads with large turndown ratios that are required for a rapidly changing environment. Many residential VCS, such as those found in home air conditioners or refrigerators/freezers, operate with an on-off control system where the compressor either runs at a constant speed or is off. Thus, the temperature is controlled by modulating the duty cycle. In these systems, it is desirable to provide peak cooling at the highest efficiency during the on periods, thus minimizing the operating time. Another architecture commonly used by refrigeration systems found in large supermarkets uses multiple parallel compressors, where additional compressors are engaged during peak load periods. Automotive VCS compressors provide capacity control with either variable displacement or variable speed. The majority of these VCS only control to one or two temperature set points.

There is clearly a need for research and development of VCS for advanced aircraft. The INtegrated Vehicle ENergy Technology (INVENT) Program of the U.S. Air Force is developing technologies that will enable an energy optimized aircraft which has an adaptive thermal management system capable of responding to dynamic thermal loads, changing flight regimes, and available heat sinks to achieve the greatest platform-level performance (Iden, 2012; Warwick, 2012). In support of the INVENT initiative, the Air Force Research Laboratory has constructed the Vapor Cycle System Research Facility (VCSRF) that is dedicated to the study and development of VCS control and operation.

Numerous past studies have considered various control methods for VCS. The majority of these studies are concerned with controlling evaporator outlet superheat and with instabilities at various relative capacities or low values of superheat, less than 6 °C (Elliot and Rasmussen, 2010; Rasmussen and Larsen, 2009; Stoecker, 1966). These papers typically link peak system or evaporator performance with capacity. They point out that peak capacity is achieved when the superheat is near zero for a pure refrigerant. However, most compressors are intolerant of any liquid ingestion. Hence, there is a desire for tight, precise control of the evaporator outlet superheat to prevent compressor damage while maintaining peak capacity. Precise control at low superheats can be problematic due to non-linearities inherent in these systems, which can be further confounded by the presence of compressor lubrication oil (Al-Rashed, 2011; Lottin, 2004; Martz and Jacobi, 1994). As Lottin (2004) showed previously, the value of apparent overheating (superheat) for peak COP can vary with the lubrication oil fraction of the mixture. Hughes et al. (1980) also showed that detrimental effects to evaporator performance due to lubrication oil can be much