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THE DESIGN AND TESTING OF THE LSSIF ADVANCED THERMAL CONTROL SYSTEM

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Abstract

The Life Support Systems Integration Facility (LSSIF) provides a platform to design and evaluate advanced manned space systems at NASA Johnson Space Center (JSC). The LSSIF Early Human Testing Initiative requires the integration of such subsystems to enable human occupancy of the 6 meter chamber for a 90 day closed volume test. The Advanced Thermal Control System (TCS) is an important component of the integrated system by supplying coolant to the subsystems within the chamber, such as the Air Revitalization System. The TCS incorporates an advanced high efficiency, heat pump to reject waste heat from the chamber to an external sink or "lift" temperature that emulates a Lunar environment. The heat pump is the High Lift Heat Pump, developed by Foster-Miller, Inc., and is the main test article of the TCS. The heat pump prototype utilizes a non-CFC refrigerant in a design where the thermal requirements exceed existing terrestrial technology. These operating requirements provide a unique opportunity to design and test an advanced integrated thermal system and the associated controls. The design, control, and systems integration of the heat pump and the TCS also have terrestrial technology application.

This paper addresses the design of the TCS and the heat pump, along with the control scheme to fully test the heat pump. Design approaches utilized in the LSSIF TCS are promoted for implementation in terrestrial thermal systems. The results of the preliminary thermal and fluid analyses used to develop the control of the thermal systems will also be discussed. The paper includes objectives for the 90 day human test and the test setup. Finally, conclusions will be drawn and recommendations for Earth design application are submitted.

Acronyms

ATCS	Advanced Thermal Control System
CCHX	Cooling Cart Heat Exchanger
CFC	Chlorofluorocarbon
CHX	Condensing Heat Exchanger
CWHX	Chilled Water Heat Exchanger
EHT	Early Human Testing (Initiative)
ETCS	External Thermal Control System
FLUINT	Fluid Integrator
HLHP	High Lift Heat Pump
HVAC	Heating, Ventilating, Air Conditioning
Hx	Heat Exchanger
ITCS	Internal Thermal Control System
JSC	Johnson Space Center
LSSIF	Life Support Systems Integration Facility
NASA	National Aeronautics and Space Administration
SHX	Supplemental Heat Exchanger
SINDA	Systems Improved Numerical Differencing Analyzer
TCS	Thermal Control System
4BMS	Four-bed Molecular Sieve

Introduction

When permanent bases are established on planetary surfaces or in Earth orbit, advanced regenerative life support systems will be required to reduce consumables and the overall mass of the outpost. While a variety of life support systems have been proposed, testing has been limited and has focused on individual, not integrated systems. As such, a new project was initiated by the Crew and Thermal Systems Division of the JSC to design, build and test an advanced, integrated, regenerative life support system.

One major subsystem of the LSSIF is its thermal control system. This system cools various components and provides cooling for a portion of the crew air by using an advanced control scheme, an advanced heat pump and an environmentally safe working fluid. The heat sink for heat pump simulates a lunar environment, and tests the heat pump's ability to handle varying loads.

While the LSSIF is in the early stages of build-up, its advanced thermal control system, especially the heat pump will have many terrestrial applications. For example, household and office cooling, closed environment cooling, and thermal control systems will all benefit from this research.

TCS Layout

A system schematic of the TCS is shown in Figure 1, depicting the interface of the heat pump between the Internal and External TCS. The major heat transfer devices selected for each loop are also depicted in the diagram along with the supply temperatures to (or from) the associated TCS. The Internal TCS components provide a heat source for the heat pump, and are representative of a thermal design integrated with other life support systems within the chamber. The designed External TCS components remove the dissipated load from the heat pump, and emulate the environmental conditions experienced by an advanced planetary outpost. The supply temperatures in Figure 1 represent the set points from which control is conducted and system performance is measured. The Internal TCS cannot perform complete temperature and humidity control, and the existing HVAC system within the chamber removes the residual heat and provides crew comfort.

Internal TCS

The Internal TCS acquires waste heat within the chamber utilizing the Condensing Heat Exchanger (CHX), Four-bed Molecular Sieve (4BMS), and Electronic Coldplates. The heat pump then transfers the internal load to the external loop. The CHX is an air-to-water counter flow heat exchanger, and depicts an air conditioning unit that removes residual heat transferred to the chamber air. The CHX cannot remove the total chamber heat load, and an existing chamber HVAC unit is employed to transfer the remaining load. The CHX does supply the majority of the 5 kW load to the heat pump. The CHX air side outlet also supplies the Air Revitalization System 4BMS with the cooler, dryer air, at ~10 °C. The 4BMS removes carbon dioxide from the chamber, and rejects heat to the internal coolant loop through an internal air-to-water heat exchanger. Thus, the 4BMS is directly dependent on a proper functioning CHX and heat pump through both mechanical and computer controlled interfaces. This integral operation represents the purpose of testing advanced systems in the LSSIF. The design approach employing direct cooling to the fluid increases the efficiency over conventional designs that dissipate the heat to the surrounding air, then acquire the heat employing air flow to the air conditioning unit (or HVAC).

The design in Figure 1 includes a Supplemental Heat Exchanger (SHX) that transfers the heat directly to the facility chilled water system. This

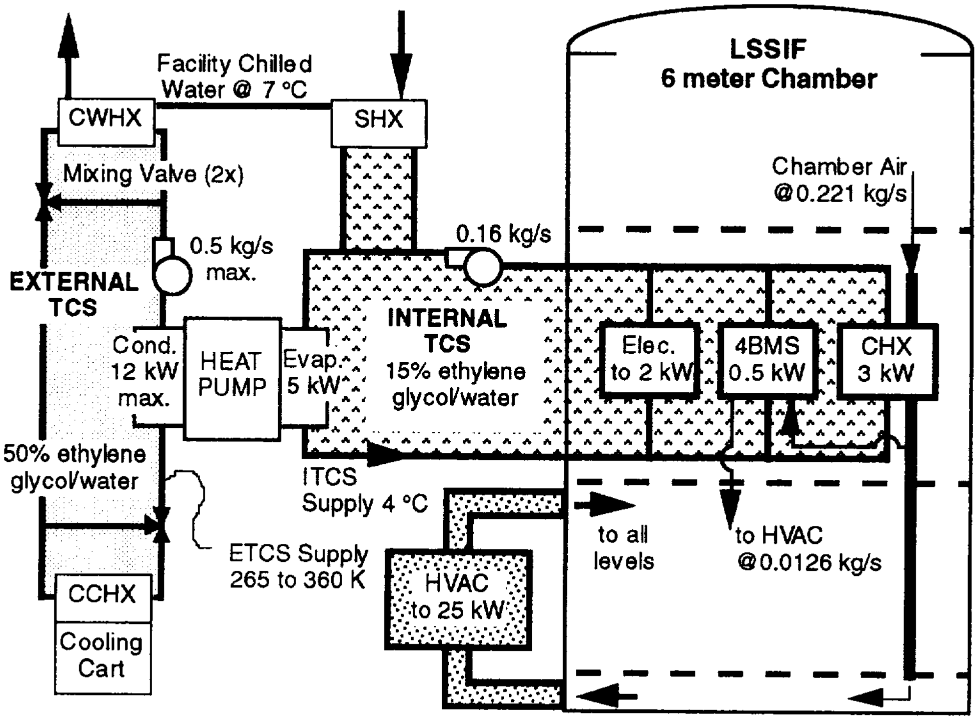

Figure 1. Schematic of LSSIF Advanced Thermal Control System.

heat exchanger operates in a contingency mode to cool internal loop components in the event of ETCS or heat pump outage. During normal operation of the TCS, the SHX is by-passed.

External TCS

The External TCS consists of the chilled water and cooling cart heat exchangers to remove the heat pump load. Pneumatically automated mixing valves control the supply temperature to the heat pump based on the Lunar thermal profile. The external supply or "lift" temperature profile is shown in Figure 2. The design includes redundant heat exchangers and mixing valves to serve as backup for single point failures. Flow in both the internal and external loops is supplied by adjusting pump speed. This increases pump life over conventional flow control employing by-pass plumbing or restrictive valving.

Heat Pump

The TCS design, control, and test setup are focused on the main TCS test article, The Foster-Miller, Inc. High Lift Heat Pump. Figure 3 shows a schematic of the heat pump design, and a pressure-enthalpy diagram is depicted in Figure 4. The design includes the basic refrigeration components of an evaporator, compressor, condenser, and expansion valve. The design adds compressors and heat exchangers to increase the heat pump efficiency for the extreme range of sink temperatures, 265 to 360 K.

The heat pump is designed to reject the Internal TCS heat load to a varying external loop supply temperature. For lift temperatures below the 4 °C internal supply, a direct heat exchanger provides cooling between the two loops, since the temperature of the external environment falls below the internal fluid temperature. This heat exchanger and associated plumbing were not depicted in Figure 3. The heat pump is in a standby mode (no work) at the low lift temperatures. As the external loop supply temperature increases over the profile, a first stage compressor is powered, and "lifts" the internal heat to the sink temperature by the addition of work. This is performed by varying the compressor speed, and as the external temperature continues to rise, the speed of the first of three is increased to a maximum, then the next compressor is energized. These steps continue until all three first stage compressors approach their maximum speed, then power is supplied to a second stage compressor. The process repeats, until the heat pump provides a maximum work load of 7 kW. Thus, 7 kW of work is required for the 5 kW nominal internal load for the maximum external supply temperature of 360 K, and a total load of 12 kW is applied to the external loop. For a decreasing profile, the process is reversed. The control logic for the heat pump is internal, and performs these required functions to continuously supply the internal loop with a temperature of 4 °C.

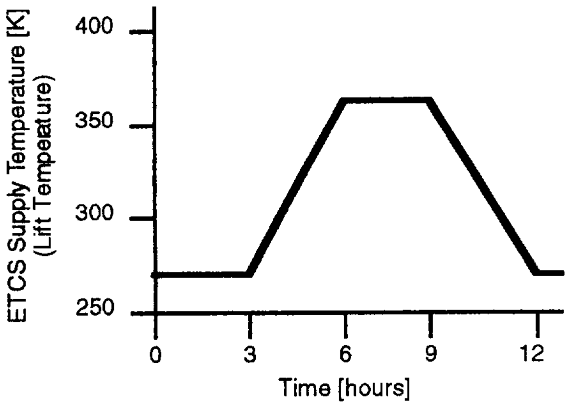

Figure 2. ETCS Supply Temperature Profile.

Controls

The TCS control scheme is automated through the LSSIF central controller, a GE Fanuc. The GE Fanuc controls the TCS and other life support systems in the chamber, plus acquires data to evaluate system performance, real time and for post test analysis of subsystem components. The chilled water heat exchanger controls temperatures in the high temperature range, above 305 K, while the cooling cart delivers the required external loop supply temperatures at the lower range, below 280 K. In the moderate or transition temperature range, from 280 to 305 K, both the cooling cart and chilled water heat exchanger are operational. The first mixing valve supplies constant flow to the chilled water heat exchanger, while the second valve controls the remaining load by adjusting the flow to the cooling cart. In the event of cooling cart failure, flow is diverted to the chilled water heat exchanger, and the test is continued. The associated mixing valve portions the flow to the heat exchanger through a 4-20 mA signal. The LSSIF GE Fanuc controls this signal based on the measured external supply temperature against the value of the thermal profile (Figure 2). The controls for the heat pump are internal (a second GE Fanuc) to this equipment and independent of the LSSIF GE Fanuc. Therefore, the controls by the heat pump and the GE Fanuc may counter each other causing a runaway external supply temperature. With the inclusion of pauses in the external loop algorithm and the signaling of a single mixing valve based on

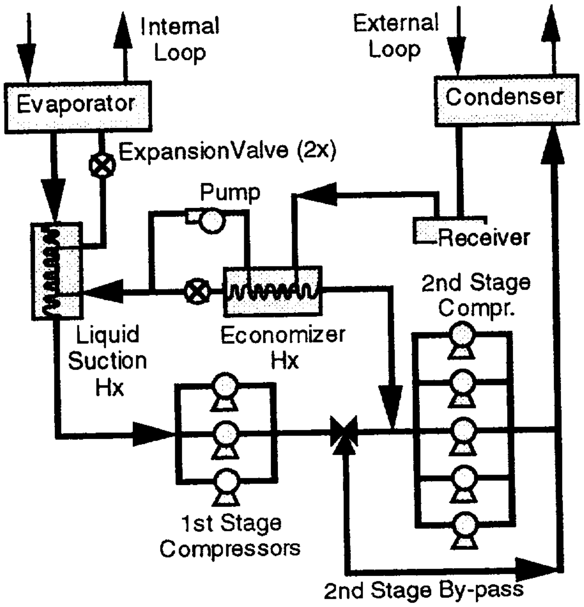

Figure 3. High Lift Heat Pump Schematic.

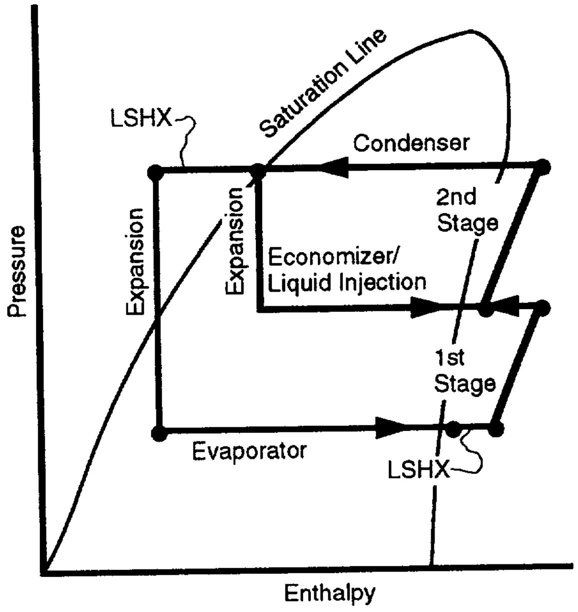

Figure 4. Heat Pump Thermodynamic Cycle.

the external supply temperature this dilemma is avoided.

Test Objectives & Test Setup

The design and testing of the TCS are centered on the following TCS test objectives:

- Show heat pump supply to the internal loop is maintained at 4 °C
- Demonstrate heat pump high temperature lift / high heat load capability
- Establish minimum and maximum loads on heat pump (ETCS and ITCS)
- Determine heat pump control response to transient conditions by performing Lunar environment profile
- Show heat pump refrigerant / component compatibility

Secondary test objectives include demonstrating continuous CHX performance and establishing the effectiveness of the electronic coldplate advanced interfaces. The main test objective of the LSSIF EHT Initiative is to provide life support through the integrated systems over the 90 day human test.

Figure 1 establishes the basic TCS test setup depicting the devices within the chamber and in the high bay of Building 7 at NASA-JSC. The LSSIF GE Fanuc and the heat pump GE Fanuc provides automated control and data acquisition for the subsystems, although the two computers are not directly linked. Since the computers provide independent control to their associated systems, an external loop test was devised to show the proper controls of the ETCS prior to heat pump integration. A 12 kW immersion heater replaces the heat pump in Figure 1 to provide a heat source to the ETCS for this test. Upon completion of the external loop test, and the demonstration of proper control of the supply temperature over the profile, the heat pump will be incorporated into the TCS. Control issues then become distinguishable between the heat pump, ITCS, and ETCS.

Numerical Modeling

The performance of the TCS design was validated by thermal and fluid analyses to show the proper operation of the TCS components and that the design meets the test objectives. The temperature and pressure of modeled components were solved using the Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA/FLUINT) software based on the thermodynamic fluid states. Detailed thermal modeling of components using resistor-capacitor methods (SINDA) was not performed.

capacitor methods (SINDA) was not performed. Thermal and fluid surveys were conducted to optimize the system design and identify potential thermal issues. From the basis of the surveys, specific hardware was identified and an external loop control scheme was developed to automate the variable supply temperature to the heat pump.

Figure 5 and 6 show the results of the ETCS model. The figures indicate control of the External TCS heat load and, hence, the supply temperature over the range of the profile by delivering the proper mass flow to the associated heat exchanger through the mixing valve. The ETCS and ITCS models were also utilized to predict component pressures and perform design trades of line lengths and diameter to optimize pump sizing. The pumps in both the internal and external loops deliver the required flow rates at pump heads of ~30 meters.

A heat pump efficiency of 48% of an ideal Carnot cycle was computed for the maximum supply temperature (360 K). This value provides a measure of the heat pump performance and design capability. This heat pump design provides an improvement over conventional refrigeration systems with sink temperatures that are much greater than current environments.

Terrestrial Applications

The terrestrial applications of the LSSIF TCS are aimed toward continuous enclosed operating systems. A variety of such systems include large office buildings, clean rooms, operating rooms, and enclosed agricultural green houses. These facilities operate, in general, continuously under high heat loads. Additional design applications of enclosed thermal systems include aircraft, military tanks, submarines, and survival shelters where the availability of outside air exchange is limited and extreme thermal transients are possible.

The design approach of the Internal TCS is typical of enclosed systems, particularly for military designs. Components rejecting high heat loads should be directly attached to the coolant loop to minimize the inefficiencies associated with conventional air-to-water transport systems, although a condensing heat exchanger is generally required for crew comfort. Scars are required for additional systems and as technology advances.

The External TCS depicts an advanced control scheme through the interface of the GE Fanuc with the Internal TCS, the heat pump, and additional systems in the LSSIF. Commercial

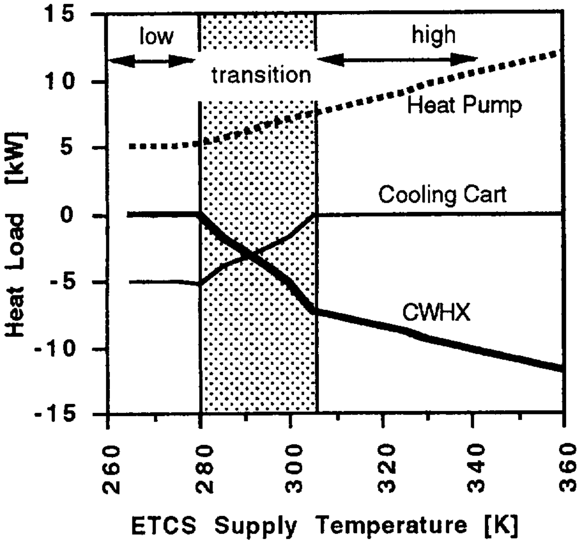

Figure 5. Analysis Results. Component Heat Loads vs. Supply Temperature.

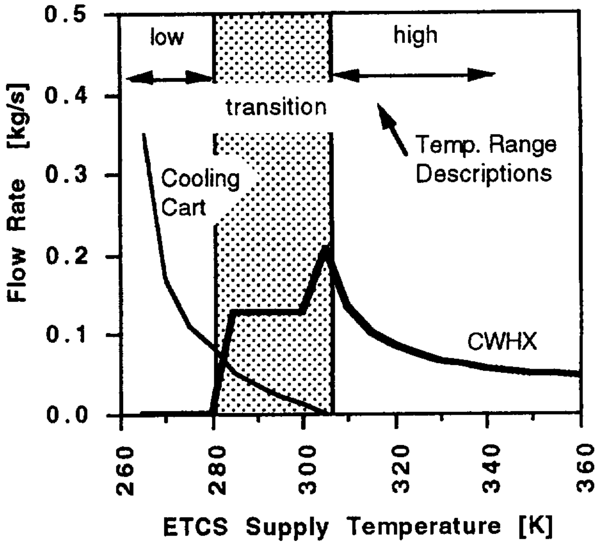

Figure 6. Analysis Results. Heat Exchanger Mass Flow Rates vs. Supply Temperature.

applications using this interaction include the air conditioning of large office buildings where the HVAC system is a critical part of the design. The computer control of each component in the thermal system can project the optimum control under the load requirements for a particular design scenario, thus avoiding the on and off cycling of these systems.

The High Lift Heat Pump provides numerous applications that directly correspond to terrestrial designs. As previously mentioned, the automated control of the heat pump is beneficial to indicate the logistics of an integrated system. The heat pump also determines if the load can be rejected directly to the environment or if additional work by the compressors is required. By varying the compressor work or directly rejecting heat to the environment, a saving of energy results. This design method is also beneficial to commercial air conditioning systems, such as in a home or office where control is obtained by cycling the system on and off. Again, by varying the speed of the compressor, an optimum rejection temperature may be obtained as measured against the work input, causing energy and cost savings. Also, as the rejection temperature is increased, the design margins would diminish the size of the condenser unit, thus resulting in additional space and cost savings. The size (and space) saving directly corresponds to weight which is of particular interest to military applications.

The heat pump operates using an environmentally safe refrigerant, R123, and commercial hardware. This provides additional data about commercial hardware performance with the "new" refrigerant, and at severe operating temperatures. The design of systems and prolonged usage of the refrigerant provides beneficial data to the design engineer and refrigeration community. The operation at high environmental sink temperatures and high heat loads are also advantageous to the design of terrestrial systems since these extremes have not been accomplished prior to this design.

Conclusions

The design of an Advanced Thermal Control System to be tested in the LSSIF has been presented showing applications in terrestrial systems. The High Lift Heat Pump provides a mechanism to control internal fluid loop temperatures while rejecting the load to temperatures that approach 100 °C. The heat pump utilizes automated control to operate efficiently with an environmentally safe refrigerant, R123. These high operating temperatures and this fluid have not been studied or used in current heat pump designs and these designs could lead to more energy efficient and environmentally safe heat pumps..

Terrestrial enclosed systems are the main benefactor employing a LSSIF thermal design. Design of a continuous operating refrigeration system using computer control to vary compressor speed provides an efficiency improvement over conventional on and off technologies. Direct interface of high load components to the fluid loop was also introduced as a method of diminishing the inefficiencies of air-to-water transport systems.

The integration of advanced space systems for life support, including a Thermal Control System, have many terrestrial applications. Once the build-up of the LSSIF is completed, these and other applications will become more readily apparent.

Acknowledgments

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