INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

THE DEVELOPMENT OF THE THERMAL CONTROL SYSTEM FOR A SPACE EXPERIMENT

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Keywords: thermal control system, international space station, fluid science laboratory, experimental container

1. Introduction

The described system belongs to an experiment under the scientific coordination of Prof. Dr. Ch. Egbers from the department of Aerodynamics and Fluid Mechanics at the Brandenburg University of Cottbus, Germany, that will be launched in 2005 to be integrated into the Fluid Science Laboratory of the International Space Station.

The International Space Station (ISS), which has been developed and built by 18 nations, represents a new and unique platform allowing research under permanent microgravity conditions. From 2001 onwards an increasing number of experiments from different disciplines have been performed on the ISS.

The Fluid Science Laboratory (FSL) is one of several modular laboratories on board the, so-called, COLUMBUS module, the major European contribution to the ISS, which is expected to be launched in 2005. The FSL will allow fluid science research in the absence of gravitational influence. The gravitation is prevalently a disturbing factor of fundamental scientific experiments e.g. crystallisation processes or basic fluid research.

The FSL is a multi-user facility for scientific experiment's, built up of different modular sub-units for the control and monitoring of the individual exchangeable experimental module called Experimental Container, which is a common envelope for all experiments with standard interface options to the facility itself in order to be accommodated within the FSL. This entails, that each experiment has a specific set of requirements, such as mass, shape, optical field of view, observation direction, electrical, thermal and functional interfaces [ESA-ESTEC, Alenia Aerospacio 1999].

The Experimental Container "GeoFlow" contains an experiment that allows the investigation of fluid flows within a rotating spherical gap under imposed electrohydrodynamic and thermal fields. The research focuses on so-called "geophysical fluid flows" which are of particular importance for a number of problems such as the explanation of the mantle convection of the earth, the flow in a planet's interior or the behaviour of planet's atmospheres. The comprehension of these spherical Couette flows will also help to improve engineering tasks such as spherical bearings or centrifugal pumps [Egbers C., Brasch W., Sitte B. Immohr J and Schmidt J-R. 1999].

2. The experiment setup

The core of the experiment is a fluid cell with an outer diameter of 80 mm that consists of a polished hard metal inner sphere, acting as a spherical mirror for optical observation, which is surrounded by two concentric glass spheres. The glass spheres form two separated gaps, filled with silicone oil, whereat the inner gap is the observed area and the outer gap is used for temperature gradient control. The adjustable thermal gradient is induced by heating the inner sphere and cooling with a fluid flow across the outer gap of the cell. This involves two separated fluid loops which have to be controlled separately. The entire fluid cell can be rotated with a maximal rate of 120 rpm.

The expected flow patterns strongly depend on the temperature gradient, the rotating velocity, the fluid viscosity and the gap width. The different parameters will be varied during the experimental time. It is designated to accomplish approximately 120 parameter variations with each of 9 experiment cells, all having the same outer diameter. With these experiment cells 3 different gap widths and 3 different viscosities are processed sequentially. The gap widths are varied by changing the diameter of the inner sphere and the viscosities are changed by filling the cells with different silicone oils [ESA-ESTEC 2001]. The examination of the fluid flow will be conducted by means of FSL observation possibilities.

The electrohydrodynamic field is a central force field, similar to the gravity field acting on planets, established through the dielectrophoretic effect that is caused by applying high voltage with up to 10 kV to the observed area of the cell.

To comply with the extensive safety requirements the Experimental Container is filled with the electrical isolating gas Sulphur Hexafluoride (SF6). This gas not only has a very high dielectric strength but also thermal properties that are helpful in this application. Due to the high density of SF6 turbulent flow is reached at lower flow velocities. This abrogates negative effects like the lower heat capacity and the lower thermal conductivity.

Due to the numerous exchanges demanded of the experimental cell that are required for parameter variations, the possibility must be given to carry out this task rapidly on ground. To allow this exchangeability without opening any fluid circuits, a so-called Line-Replaceable-Unit (LRU), a cohesive unit concept that contains the fluid cell and its corresponding infrastructure, has been developed.

Generally, the Geoflow Experiment can be split up into two parts: the Line-Replaceable-Unit and its respective support structure.

The LRU is mounted to the support structure that provides the rotational drive, the optical alignment between the fluid cell and the FSL for optical diagnostics and the reliable heat dissipation towards the FSL thermal control system.

2.1 The LRU thermal control system

The LRU thermal control system consists of an inner sphere fluid heating loop and an outer gap cooling loop with an analogous structure. Each loop is composed of a Thermo-Electrical-Cooler (TEC) coupled to a heat exchanger (HX) for heating / cooling the fluid which is circulated by pumps. The TECs are mounted on top of a heat spreader plate with a diameter of 180.5 mm that constitutes the support structure of the fluid cell.

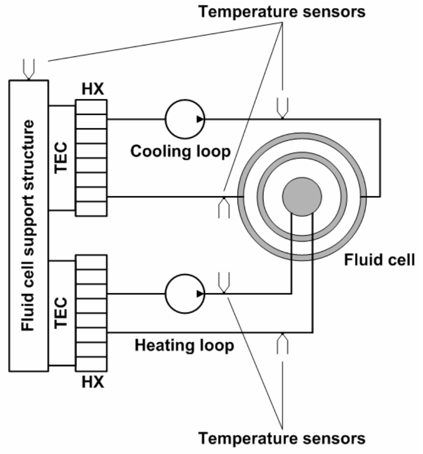

Figure 1. A diagrammatic representation of the LRU thermal control system

The fluid cell support structure also contains the infrastructure of the cell which is the tubing for the media transport, the heat exchangers, metal bellows for volume compensation, evacuation and filling valve and the pumps. Two temperature sensors are placed at the inlet and outlet of each heat exchanger. The sensor at the heat exchanger outlet is used for temperature control. The temperature difference between the inlet and outlet of the heat exchanger is, at known fluid flow rates, a measure of the heat input respectively the heat removal of the thermal control unit.

Adjustable with an accuracy of 0.1K, the maximum cell temperature gradient to be achieved is 10K. Of minor importance for the experiment result is the absolute temperature of the media which is thus chosen close to the ambient temperature of 25°C. First analyses showed that the power consumption of the LRU and with that the energy dissipated to the fluid cell support structure has a maximum value of 50 W which has to be passed on the water cooling system of the FSL, called the Secondary Water Loop Assembly (SWLA).

2.2 The LRU support structure thermal control system

The LRU support structure thermal control system is designed to remove the heat energy generated by the experiment from the fluid cell support structure to the water cooling circuit of the FSL. To accomplish this it consists of two heat exchangers interconnected by hoses for transportation of the SF_6 gas flow.

The first heat exchanger is an annular fin air heat exchanger and is an integral part of the LRU support structure. It consists of a circular heat spreader plate with a diameter of 190mm to which concentric cylindrical fins are attached. To the LRU support structure axis a slip-ring assembly is mounted for the power and data supply of the fluid cell assembly. This results in a very constricted remaining area for the fins as the inner diametrical 100mm are not useable. The LRU support structure will be manufactured out of one part of aluminium to assure maximal heat transmission from the heat spreader plate to the fins.

The fins are cooled by the gas flow which is generated by two fans attached to the second heat exchanger called the heat exchanger turret. The gas flow through the heat exchanger turret is cooled down by TECs that can be controlled to allow the accurate adjustment of the LRU support structure temperature. The TECs are coupled to water cooled cold plates that are connected to the FSL water cooling loop.

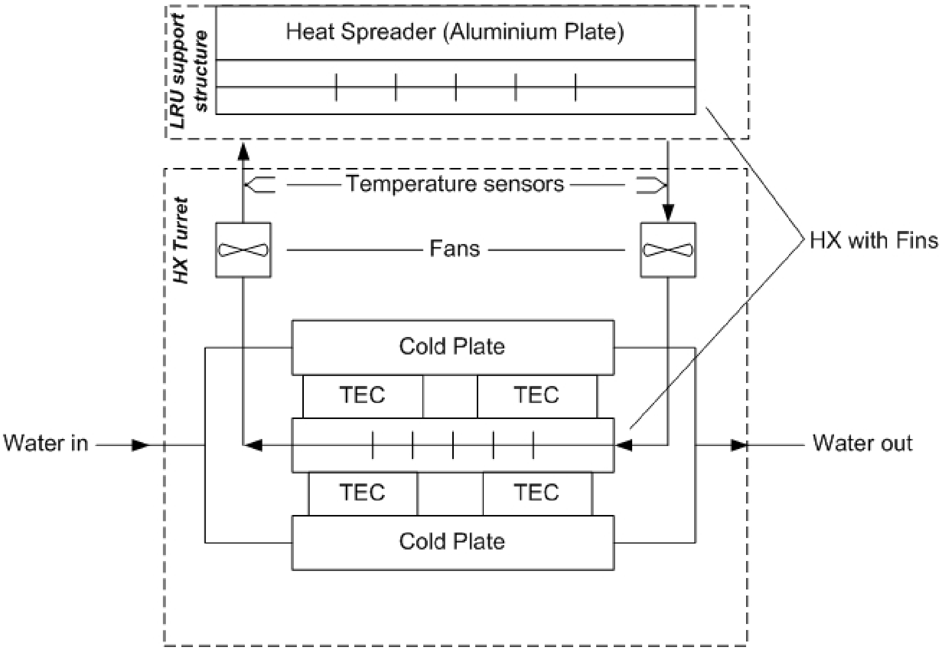

Figure 2. A diagram of the LRU support structure thermal control system

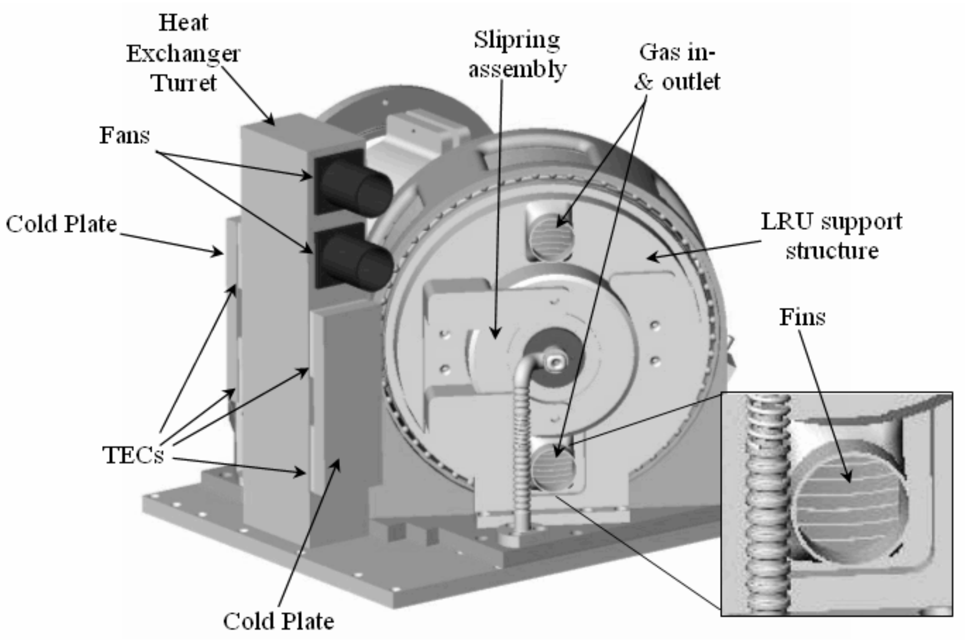

Figure 3. CAD picture of the LRU support structure thermal control system, shown without hoses and electrical harness

2.3 A closer look on the design of the LRU support structure thermal control system

Due to the very constricted volume predetermined by the Experimental Container dimensions the main emphasis of the LRU support structure thermal control system development is high cooling efficiency at an exceedingly compact design. The expected problems are provoked by the character of forcing the gas through the rotating fins to produce homogenous heat dissipation on the LRU. It is expected that the rotation of the system influences the homogenous cooling behaviour of the symmetrical gas flow circuit. The cooling efficiency must be of the same order during different velocities to allow reliable heat removal.

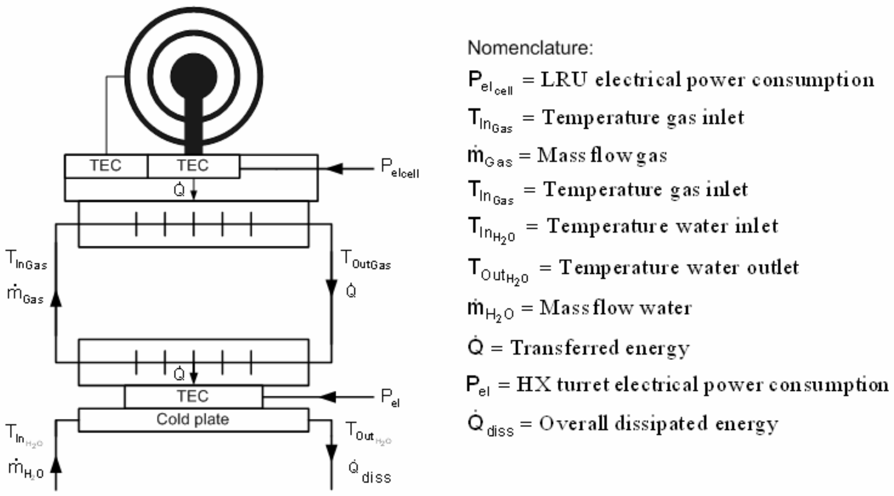

Figure 4. The thermal control system budget map

The thermal control system budget map shows the required parameters required for the development of the LRU thermal control system. It can be seen that the overall dissipated heat energy is the sum of all electrical power consumptions. The basic conditions to transport the energy can be calculated by following equations [VDI-Wärmeatlas (1988)]:

$$\dot{Q} = P_{el_{cell}} = \dot{m}_{Gas} \cdot c_{p_{Gas}} \cdot \Delta T_{Gas} \tag{1}$$

$$\dot{Q}_{diss} = \dot{Q} + P_{el} = \dot{m}_{H_2O} \cdot c_{p_{H_2O}} \cdot \Delta T_{H_2O} \tag{2}$$

These equations show that the design drivers are the mass flow, the specific heat capacity and the temperature difference of the cooling medium. The mass flow is primarily produced by the fans which have to be selected accordingly, the specific heat capacity is a constant of the medium and the temperature difference between incoming and outgoing medium is produced by the heat exchangers. The temperature difference in this application is actively produced by the heat exchanger turret which needs electrical power for cooling and passively produced by the LRU support structure heat exchanger which passes the heat to the cool gas flow which is then heated up.

The mass flow in the entire system is affected by the pressure loss the system produces which is a function of the design.

To avoid the risk of a hydraulic short-circuit inside the first heat exchanger, which would drastically decrease the cooling efficiency, and to assure uniform heat removal the design is done in such a way that the average flow speed between all fins is the same. By varying the distance between the fins from small on the inner area to large on the outer area the hydraulic resistance represented by the channels and therefore the average flow speed between them is optimised for maximum heat removal.

Using an iterative method, varying channel widths are determined in order to make the average fluid speed inside each channel proportional to the central radius of its respective channel. Considering also manufacturing limitations this leads to a geometry consisting of:

- seven concentric cylindrical fins,
- a fin height of 20 mm,
- a fin thickness of 1.3 mm,
- and a specific set of channel widths:
  $inside \rightarrow 3{,}1mm - 3{,}5mm - 4{,}1mm - 5{,}0mm - 6{,}3mm - 8{,}1mm \leftarrow outside$

The main geometry of the heat exchanger turret is non-variable. It is a matter of achieving as much heat transferring surface as possible within the available volume of H=244 mm, W=42 mm and D=62 mm without increasing pressure drop too much. An iterative calculation process leads to a fin geometry of:

- eight straight fins
- a fin height of 25mm
- at 3,1mm from each other
- and an overall mean flow path of 400 mm

With the geometry of the first and the second heat exchanger and the expected volume flow produced by the fans known, the governing maximum respectively minimum temperatures at which the system will operate are determined:

$$\overset{\dot{Q}}{50W} \Rightarrow \underbrace{\overset{T_{TEC,cold}}{-7^\circ C}}_{achievable} \Rightarrow \underbrace{\overset{T_{HXT}}{3.3^\circ C} \Rightarrow \overset{T_{SF_6,low}}{5.5^\circ C} \Rightarrow \overset{T_{SF_6,high}}{11.6^\circ C}}_{required} \Rightarrow \overset{T_{\text{support structure}}}{23^\circ C}$$

The set of temperatures shows the lowest achievable temperature the selected TECs can supply given the certain heat load, the required temperature of the heat exchanger turret fins, the temperature of the gas flow leaving the heat exchanger turret and the temperature of the gas flow leaving the heat exchanger of the LRU support structure to remove the 50 W and while maintaining a constant LRU support structure temperature of 23°C:

3. Conclusion

During the Phase B study a preliminary design for the thermal control system of an experiment for the Fluid Science Laboratory was developed and analysed. The basic requirements could only be fulfilled by using optimised solutions for the heat exchangers. The analysis could only be done by using simplifying assumptions and simplifications as there are a number of uncertainties which cannot be covered by calculation. This is especially due to the fact that it is difficult to estimate pressure losses and that the isolating gas Sulphur Hexafluoride is being used for which some results only can be assessed. Therefore a breadboard phase will have to be initiated, during which the performance of the different subsystems of the thermal control system will be demonstrated on laboratory level, before the full development phase will start.

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