N90-17922

DEVELOPMENT OF AN INFRARED IMAGING SYSTEM FOR THE SURFACE TENSION DRIVEN CONVECTION EXPERIMENT

Alexander D. Pline

NASA Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

An infrared imaging system is used to quantify the imposed surface temperature distribution along a liquid/gas free surface in support of the Surface Tension Driven Convection Experiment, a planned Space Transportation System flight experiment. For ground-based work a commercially available instrument was used to determine the feasibility of using this type of imaging system for this experiment. The ground-based work was used as a baseline for compiling specifications for a flight qualified imager to be designed, fabricated, tested and qualified for flight. The requirements and the specifications for the flight model are given along with the reasons for departures from the ground-based equipment. The flight qualification requirements discussed are a representative sample of the necessary procedures which must be followed to flight qualify diagnostic equipment for use aboard the STS. The potential problems and concerns associated with operating an imaging system on orbit are also discussed.

INTRODUCTION

A non-contact surface temperature measurement system is being developed in response to the need for quantitative, full field characterization of the resulting surface temperature distributions during the Surface Tension Driven Convection Experiment (STDCE). The STDCE is a space flight experiment to study thermocapillary flows, during the USML-1 Spacelab mission. The current STDCE schedule is to have flight hardware ready for shipment by April 1, 1991 for the USML-1 Spacelab mission planned for March 1992. Thermocapillary flows are generated by a thermally induced surface tension variation which acts as a surface tractive force along a liquid/gas free surface from regions of low surface tension (high temperature) to high surface tension (low temperature).

During the STDCE a 10 cm diameter by 5 cm deep cylindrical container of silicone oil is heated centrally either internally or externally while the resulting thermocapillary flows are visualized by illuminating a cross section with a sheet of light. The internal heating case (or CT experiment) uses a 1.1 cm diameter by 5 cm height resistance heater (heated wall) placed centrally in the test cell (cooled wall) to establish the temperature gradient along the free surface. For the externally heated case (CF experiment) the resistance heater is removed and the free surface heated using focused CO_2 laser radiation.

Because liquid/gas free surfaces are ubiquitous to containerless processes, the understanding of surface tension driven flows in reduced gravity as well as terrestrial gravity is important in the commercialization of containerless materials processing techniques.[1] The surface temperature distribution is a critical parameter for these types of flows as it is the driving force.[2,3] In reduced gravity, a liquid/gas free surface may not be stationary due to small accelerations, called g-jitter, aboard the vehicle. Consequently, when the thermal boundary layer along the free surface is thin contact surface temperature measurement methods are sensitive to these disturbances. Therefore, development of a non-contact temperature measurement system to quantitatively characterize the thermal signature is an essential part of the development of the STDCE.

The system development is divided into two phases: a testing phase, to study the feasibility of using a commercially available infrared imaging system to characterize the surface temperature distributions, and a flight hardware development phase. The testing phase was based on the science objectives put forth by the Principal Investigator, S. Ostrach and the Co-Investigator, Y. Kamotani, both of Case Western Reserve University, in the STDCE Science Requirements Document.[4] An absorption study of silicone oil was conducted to determine the most appropriate operating wavelength for the imager and the surface layer thickness measured by the imager. Based on study results, the Model 600 Infrared Imaging System was purchased from Inframetrics Inc. Testing was conducted using this system to determine its accuracy compared to thermocouple measurements and numerical calculations as well as an effective emissivity for these experimental conditions (reference 5).

The flight hardware development phase consists of procuring a space flight qualified infrared imager. In addition to the technical specifications derived from the testing phase, the Statement of Work (SOW) in the Request for proposal (RFP) also contains a plethora of requirements which *the manufacturer* must meet in order to fly on the Spacelab. These requirements include related development work, design reviews, vibration levels, safety and qualification/acceptance testing which must be met within the constrained schedule associated with the USML-1 deadlines. This procurement will result in a fully tested and space flight qualified infrared imager delivered to NASA Lewis Research Center for integration with the balance of the STDCE hardware.

DEVELOPMENTAL TESTING

Science Requirements

The requirements for the surface temperature measurement system are for a full field non-intrusive measurement using a thermographic technique. The operational wavelength should be chosen so that the detected radiation comes from a region as close to the surface as possible. The spatial resolution should be less than or equal to 1 mm and the temporal resolution should 0.1 second or less. The accuracy of the instrument should be within ±5% of the ΔT between the center and side wall except near the center and wall regions where ±10% is acceptable. To satisfy these requirements, the technique should be calibrated by thermocouple measurement as well as be consistent with numerical analysis.

Absorption Study

The absorption characteristics of silicone oil must be known in order to select the operational wavelength of the imager and to determine how deep the imager "sees" into the oil. Using an infrared spectrophotometer, transmission of radiation as a function of wavelength through a variable thickness of silicone oil was measured. From this data an empirical relationship in the form of the most simplified version of Bouguer's Law was determined. The thickness of fluid which attenuates nearly 100 percent of the incident radiation in the imager operating wavelength region is called the "surface" thickness.

The transmission versus wavelength results show that silicone oil is quite transparent at wavelengths of less than 8 micrometers (μ). Therefore an imager which operates in the far infrared (8–12μ) is needed. In order to find how silicone oil attenuates radiation in this region, transmission was averaged numerically and plotted against fluid thickness. In addition transmission at 10.6μ was plotted against fluid thickness to determine the pentetration of CO_2 laser radiation. From these relationships (Fig. 1), the fluid thickness which attenuates nearly 100% of the incoming radiation is found to be 0.200 mm and 0.256 mm for the 8–12μ region and 10.6 μ wavelength respecively. Therefore, it is concluded that the "surface" the imager "sees" is 0.200 mm thick. The fact that the CO_2 laser radiation penetrates deeper than this is advantageous. If the situation were reversed, the temperature indicated by the imager would be an average over a region where a much larger temp–erature gradient would exist.

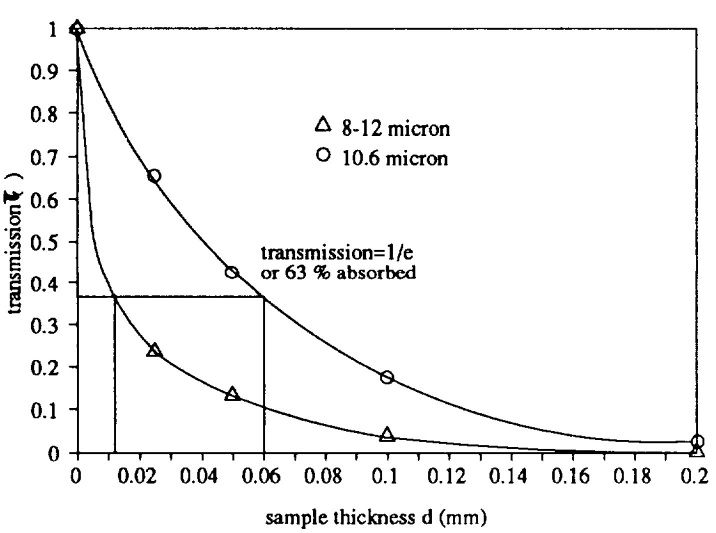

Figure 1. Transmission as a function of fluid thickness

Imager Selection

The conclusions drawn above indicate the need for an imager which operates in the far infrared. Satisfying this requirement, as well as the other science requirements, based on manufacturers specifications, the Inframetrics Model 600 and Thermal Image Processing System were purchased. The Model 600 has a spatial resolution of 2 milliradians (mr), or 0.8 mm at 40 cm working distance, and a temporal resolution of 0.033 seconds (RS–170 video frame rate). A more complete description of the Model 600 can be found in references 5 and 6.

Effective Emissivity

Because no surface is an ideal radiator, there is an emissivity (<1) associated with that surface. This emissivity value is needed as an input to the thermal image processing system to account for non–ideal radiation and reflected background radiation. Due to the lack of existing literature documenting the emissivity of silicone oil, an emissivity was determined empirically by comparison of the imager surface temperature data with other techniques. This emissivity value of 0.90 is called the "effective emissivity" because it accounts for all the non–ideal radiative properties of silicone oil only for *this imager* under *these experimental conditions.*

Accuracy

Data acquired using the infrared imaging system were analyzed and compared to thermocouple measurements and a calculated surface temperature distribution to establish the accuracy of the system for this experiment. Both heating modes used during the STDCE were analyzed.

Comparison of the three techniques is shown in Figure 2 for the maximum temperature gradient expected during the CT Experiment where the ΔT is near 50 oC. This is the most difficult (i.e. sharpest temperature gradient) CT measurement case with an input power to the heater of 17.7 W. Plotted in the figure is the surface temperature difference between the oil surface the test chamber wall against nondimensional radial position, measured with the target emissivity set to 0.90. The agreement among the three techniques for this case is ±5% of the overall ΔT excluding the near wall regions. The errors in the wall regions are ±10% of the ΔT and are caused, predominantly, by the imager spatial resolution, which is not small enough to resolve these gradients. Similar results were obtained for the CF experiment except measurement errors near the center were a result of the thinner thermal boundary layer and consequent averaging of cooler bulk fluid.

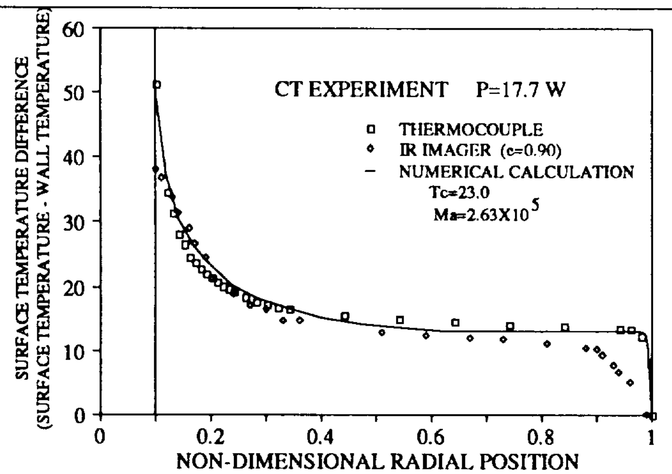

Figure 2. Comparison of numerical, thermocouple, and IR Imager surface temperature distributions for the CT Experiment when the input power is 17.7 W and Tc=23.0 C.

FLIGHT HARDWARE DEVELOPMENT

The development work described was used as a baseline from which specifications for the flight model were developed. In addition to the technical specifications, other design and qualification requirements were compiled to guide the manufacturer in the design, fabrication and testing so that the final instrument is a *fully space flight qualified* imager, which will meet all performance specifications for the STDCE and satisfy all STS requirements.

Technical Specifications

The major technical specifications of the desired imager are summarized in Table 1. Like the ground based imager it will produce an analog output in the form of an RS-170 video signal which can be recorded and analyzed after the fact. Care was given not to specify any operational characteristics particular to the commercial equipment such as the image acquisition scheme (i.e. scanners versus focal plane arrays). The intention was to procure a black box which would produce data per the specifications without regard to the operational details, because the design of a new imager or redesign of a commercial system to meet the space qualification requirements is the responsibility of *the contractor.* By writing the specifications in this manner a maximum number of manufacturers could be eligible.

The major deviations from the commercial equipment are the detector cooling, the spatial resolution and the minimum sensitivity (NETD). The liquid nitrogen detector cooling scheme used for the commercial equipment is not acceptable for space applications for obvious reasons. Both a Joule-Thompson (J-T) cryostat and a Stirling Cycle cryocooler were considered to replace the LN_2 dewar. The Stirling Cycle cryocooler was chosen because it is inherently safer than a J-T cooler while providing non-exhaustible cooling. This type of cooler is also routinely used for military applications (e.g. U.S. Army common module).

Due to errors caused by sharp temperature gradients near the side and heater walls, the spatial resolution (IFOV) specification was tightened from 2 mr for the commercial instrument to 1 mr. This increase in spatial resolution will allow the instrument to better resolve the sharp temperature gradients. The minimum sensitivity of the solicited instrument is also better than the commercial imager, improving the low temperature range sensitivity, in order to resolve small amplitude temporal thermal oscillations likely to be encountered during the STDCE.

Other specifications were changed to accommodate the STDCE packaging and STS restraints. The size specified was the maximum envelope allotted for the imager during the packaging/layout of the STDCE hardware. The 30 pound specified weight, an increase of approximately 5 times over the ground-based weight should accommodate the added weight of the cryocooler and space flight qualified structure.

The differences in electrical specifications include the input voltage, power consumption and computer interface. 28 VDC was specified as the input voltage for compatibility with the STDCE main circuit, although 12 VDC could be used because there are other 12 VDC components in the

Table 1. Major Technical Specifications

specification	flight	ground-based
spectral response	8–12 μ	8–14 μ
NETD	0.1 ^{o}C	0.2 ^{o}C
MRTD	0.1 ^{o}C	0.1 ^{o}C
detector cooling	closed cycle cryocooler	LN_2
FOV	15^{o} V X 20^{o} H	15^{o} V X 20^{o} H
IFOV	1 mr (50% response)	2 mr (50% response)
dynamic range	minimum of 48 dB	42 dB
frame rate	30 Hz (2:1 interlace)	30 Hz (2:1 interlace)
output format	RS–170 video	RS–170 video
measurement ranges	5,10,20,50,100,200 ^{o}C movable between 0 and 500 ^{o}C both man/auto select	5,10,20,50,100,200 ^{o}C movable between –20 and 400 ^{o}C + x–rng center man/auto select
Post flight		
Image analysis	similar to Thermoteknix system	Thermoteknix system
size		
sensor head	8.0"D X 9.0"W X 9.0"H	8.1"D X 4.8"W X 4.9"H
electronics	9.3"D X 10.3"W X 3.8"H	9.3"D X 10.3"W X 5.4"H
weight		
sensor head	30 lbs	6.5 lbs
electronics	7.5 lbs	7.5 lbs
power consumption	maximum of 150 watts	10 watts
input voltage	28 VDC	11–17 VDC
non–operational shelf life	2 years	NA

STDCE package. Power consumption was increased to account mainly for the added draw by the cryocooler. It is not expected that 150 W will be needed but was the maximum available. The RS–232 computer interface specified will be used to control the imager during operation. Temperature range and center temperature will be selectable or, if desired, will be set to automatic via this interface. The ground–based equipment has automatic center temperature but not automatic range selection. Automatic operation of both the temperature range and center temperature is required because of the largely automated nature of the STDCE.

Contractor Development Phases

Three phases of development are specified in the SOW. The first is the design phase. The milestones associated with the design phase are at 50% completion and at final design review. In order to assure the design concept is sound and will meet NASA requirements for design of safety critical structures, materials usage, and safety, the pertinent NASA documentation was researched and incorporated into the design and test requirements (Table 2.). From the STS point of view, safety is the most important aspect of the flight qualification procedure. This is reflected by the nature of most of these documents. If the safety guidelines for design are followed, the payload developer is assured that his equipment will not harm the STS or its crew.

In addition to the design, a safety verification plan must be presented to show the design meets these safety requirements. NHB 1700.7A outlines the requirements "intended to protect flight and ground personnel, the STS, other payloads, ground support equipment, the general public, public-private property, and the environment from payload related hazards." Not listed in Table 2 is JA-012D Payload Safety Implementation Approach, which is issued to implement NHB 1700.7A. It is not part of the contract because these requirements are the responsibility of the STDCE. The purpose of the document is to "delineate the activities leading to safety certification of instruments that constitute an STS payload for which the Spacelab Payload Project Office has management and integration responsibility."

The second phase of the development is the fabrication/inspection during which the hardware shall be built to the NASA approved design. During the third phase the space flight qualification testing will be performed in an environment similar, if not more rigorous, than that of the STS. The major tests which must be conducted for qualification are vibration, electromagnetic compatibility (EMC) and toxic offgassing. Toxic offgassing tests will insure that in the event the Spacelab module depressurizes no potentially harmful gases will be produced. EMC tests are conducted to insure that the equipment will not interfere electrically, either by radiation or conduction, with the Spacelab instruments or power bus.

Table 2. Documentation Requirements

Document #	Document Name
NHB 1700.7A	Safety Policy and Requirements for Payloads using the STS
MSFC HB 527	Materials Selection List for Space Hardware Systems
SLP/2104	Spacelab Payload Accommodation Handbook
NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion
JA-418	Payload Flight Equipment Requirements for Safety-Critical Structures
JA-016B	Payload Mission Manager Interface and Safety Verification Requirements for Instruments, Facilities, MPE and ECE on STS Spacelab Payload Missions
JSC 11123	STS Payload Safety Guidelines Handbook

In conjunction with safety, survivability/reliability testing is a prime concern of the payload element developer. Both periodic and random vibration tests are conducted to insure survivability against low frequency transient responses due to engine ignition and cutoff, separation, and docking, and random vibrations caused by the Spacelab response to acoustic noise in the cargo bay. The levels to which this imager will be subjected are found in the Spacelab Payload Accommodations Handbook (SLP/2104). Because the equipment is situated in a Spacelab rack the vibration levels at the rack/module interface are used. An example of these levels is given in Table 3. In addition to these levels, a magnification factor is added to account for amplification of the vibration levels by the rack and STDCE structure: five times above the levels shown. This magnification factor may be changed as data becomes available from the STDCE engineering model analyses using a dummy mass in lieu of the imager. Because two units will be built and tested, the first will be a protoflight-qualified unit and the second a flight qualified unit. The protoflight unit will be tested to 5 times the levels in SPAH/2104 (prototype testing), refurbished and retested to 1.5 times SPAH levels (qualification testing). This unit will be used as a spare. The second unit is tested only to qualification levels and will be the primary flight unit.

Table 3. Random Vibration Testing Levels

Frequency (Hz)	Level (g^2/Hz)		
	X axis	Y axis	Z axis
20	0.005	0.002	0.002
20–80	+3 dB/oct	+6 dB/oct	+5 dB/oct
80–200	0.02	0.015	0.01
200–2000	–4 dB/oct	–4 dB/oct	–4 dB/oct
2000	0.00093	0.00047	0.00063
comp. g (rms)	3.1	2.4	2.4
comp. g×5	15.5	12.0	12.0
duration: 60 seconds per axis			

ON–ORBIT CONCERNS

Several problems are expected which are ubiquitous to operation of the STDCE aboard Spacelab. These include the effect of direct CO_2 laser beam reflections, automatic operation of the imager and angular emissivity variations due to the curved free surface.

Because silicone oil reflects specularly, reflections from the CO_2 laser beam, directed normal to the surface, are not incident on the imager detector when the imager is positioned approximately 15 degrees from axis of the test chamber. During operation on Spacelab, however, if the free surface deforms due to g-jitter, direct reflections may be incident on the detector. The reflected flux is low ($\approx$0.4 W/cm^2) and will result in saturation of the detector resulting in data loss during this time. But, no damage of the imager will occur and if the reflections are periodic there will be intervals in which data can be analyzed.

These reflections may affect the automatic operation of the imager. During automatic operation the imager selects the temperature range and center temperature based on the maximum intensities in the field of view. If reflections cause saturation of the detector, this may, depending on the duration, influence the automatic range and center temperature selection. The time constant should be sufficiently long in order to decrease the sensitivity to this type of transient.

Thirdly, target emissivity is angularly dependent. During the STDCE tests conducted using curved surfaces, the surface normal will be between 0 and 70 degrees from the axis of the test chamber. The directional spectral emissivity predicted from electromagnetic theory as a function of emitted ray angle measured from the unit normal[7] shows that there is little variation until the angle is larger than 45 degrees. Therefore, only near the walls where the angle between the surface normal and the axis of the test chamber increases past 45 degrees will substantial measurement errors occur. Additional ground-based testing in this area is planed to fully evaluate these effects.

SUMMARY

While most of the development work is complete at this time, developmental testing is an ongoing activity. Concerns associated with operating the imaging system on orbit are being addressed as well as problems involving integration of the system with the STDCE hardware. Until a flight unit is delivered, the commercial unit will be used as an engineering model and will be integrated with the STDCE engineering model hardware.

Flight hardware development was begun in August, 1988 with the compilation of technical specifications, schedule, design and qualification requirements in parallel with the advertised announcement of procurement. The RFP was released on September 19, 1988 and responses received November 1. The contract, expected to be awarded on February 1, 1989, provides 15 months for development, design, manufacture, and qualification testing.

ACKNOWLEDGEMENTS

The author would like to acknowledge the efforts of the members of the STDCE design team for their research into the STS qualification requirements and the organization of the procurement process. David Petrarca wrote the Statement of Work for the Request for proposal for the Flight qualified Infrared Imaging System and William Coho was responsible for coordinating the entire procurement process. Also, NASA Lewis Research Center's Procurement Division was instrumental in expediting the release of the Request for Proposals.

REFERENCES

1. Ostrach, S., "Low Gravity Fluid Flows," Annual Review of Fluid Mechanics, vol. 14, 1982, pp. 314–375

2. Ostrach, S, "Convection Due to Surface Tension Gradients", COSPAR Space Research, Vol. 19, M.J. Rycroft, ed., 1979, pp. 563–570

3. Kamotani, Y. and Ostrach, S., Design of a Thermocapillary Flow Experiment in Reduced Gravity, *J. Thermophys. Heat Trans.*, vol. 1, no. 1, Jan. 1987, pp. 83–89

4. Ostrach, S. and Kamotani, Y., "Science Requirements Document for the Surface Tension Driven Convection Experiment in Reduced Gravity", Department of Mechanical and Aerospace Engineering, Case Western Reserve University., 1987

5. Pline, A., "Surface Temperature Measurements for the Surface Tension Driven Convection Expericment", NASA TM 101353, 1988

6. Lee, M., ed., Non–Contact Temperature Measurement, NASA CP–2503, 1987

7. Siegel, R and Howell, J., Thermal Radiation Heat Transfer, Mc–Graw Hill, 1972, p. 103