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# Noncontact Temperature Measurements in the Microgravity Fluids and Transport Phenomena Discipline

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## Introduction

The objectives of the efforts conducted within the Microgravity Fluids and Transport Phenomena Discipline are to develop a further understanding of fundamental theories of fluid behavior, to provide improvements in basic thermophysical property measurements, and to provide scientific and engineering data related to a wide variety of fluids-related applications/systems.

The current understanding of fundamental fluid phenomena and the determination of many basic thermophysical fluids properties is severly limited by the masking effects and/or complexity factors induced by a gravitational force field. For example, in a gravity field, the buoyancy-driven flows which arise from density gradients preclude the study and subsequent understanding of other important transport processes. Similarly, it is these buoyancy-driven flows, and other gravity induced effects such as hydrostatic pressure which compress or collapse fluid specimens, that also preclude the accurate measurement of many thermophysical properties (e.g., diffusion coefficients, or properties such as viscosity and heat capacity near the critical point, etc.). Thus a significant reduction in gravity forces and their induced effects can enable measurements and observations of phenomena/processes which are impossible in a terrestrial environment. The pursuit of systematic studies of fluids under low-gravity conditions, and the resulting increased understanding will lead to refinements in existing theoretical models and potentially even new models to describe fluid physics and transport phenomena in both normal gravity and reduced gravity conditions.

The program of activities within the Fluids Discipline has been structured to enable the systematic pursuit of an increased understanding of low gravity fluid behavior/phenomena in a way which ensures that the results are appropriate to the widest range of applications. This paper will briefly discuss this structure and also provide an overview of some of the activities which are currently underway. Of significance is the fact that in the majority of the current and planned activities, the measurement and/or control of the fluid temperature is a key experiment requirement. In addition, in many of the experiments there is the requirement that the temperature measurement be nonintrusive. A description of these requirements together with the current techniques which are being employed or under study to make these measurements will also be discussed.

## Program Structure and Status

The applications of the information and knowledge gained through microgravity or reduced gravity fluids experiments span over a wide range going from potential scientific advancement to the development of design data bases for future space-based systems. These applications can best be characterized by the following list of eight categories:

- TESTING OF FUNDAMENTAL HYPOTHESES/THEORIES
- MEASUREMENTS OF THERMOPHYSICAL PROPERTIES
- PROCESSING OF METALS AND ALLOYS
- FABRICATION OF GLASSES AND CERAMICS
- GROWTH OF ELECTRONIC MATERIALS
- BIOTECHNOLOGY
- COMBUSTION SCIENCE AND SPACECRAFT FIRE SAFETY
- SPACE-BASED FLUID/ENERGY MANAGEMENT

Experiments addressing the first two applications on the list emphasize the acquisition and application of highly specialized laboratory type data which can only be obtained under reduced gravity conditions. These data are intended to: 1) test theories which are of broad significance in fluid physics or dynamics, or in other fields of science; or 2) provide increased measurement accuracies of fundamental thermophysical properties such as the viscosity or heat capacity of a fluid near its critical point.

The remaining applications on the list generally can be classified as in-space applications since that is their focus. The resulting increased understanding of fluid behavior in these areas does however generally provide concomitant benefits for terrestrial operations. In the case of the materials processing applications (i.e., metal and alloys, glasses and ceramics, electronic materials, and biotechnology), it is important to note that virtually all of the materials are processed in their fluid state. Therefore, the understanding and control of reduced gravity fluid processes is of paramount importance to in-space materials processing research and development activities. By combustion science we specifically mean the conduct of in-space combustion experiments to further the understanding of combustion processes under terrestrial and reduced gravity conditions. Here, as in the case of spacecraft fire safety, the coupled fluid flow of the oxidizer and fuel stand out as key parameters in the ignition, flame spread, and extinction processes. Therefore, again the understanding and control of reduced gravity fluid processes become extremely important.

The last category on the list represents that one which is most directly focused on space applications in that the goal is to ultimately provide design data bases for use by space system developers. On-orbit storage, conditioning, and transport of fluids and energy through the use of fluids is pervasive in most current and future space-based systems and applications. The effectiveness and efficiency of space liquid propellant systems, thermal control devices, dynamic power systems, etc., all require a thorough understanding of fluid behavior and processes under reduced gravity conditions.

The Fluids Discipline faces a difficult, if not impossible, task in attempting to address all of the specific reduced gravity fluids issues of these applications. In general, there is a wide disparity in conditions encountered in these applications which make the number of application specific tests and the range of parameters they encompass completely unwieldy. Examine, for example, fluid temperature since it is always of importance. If it were necessary to conduct specific tests over the temperature range of the applications, the experiment test temperatures would have to vary from the extremely high temperatures of molten metals down to the near absolute zero degree temperatures of some cryogenic fluids. Fortunately, a closer examination of the large number of application specific issues reveals a much smaller set of fundamental issues involving basic fluid processes or phenomena. For example, surface tension driven convection is an important issue in both metals processing and liquid hydrogen propellant storage. It can be argued that while the temperature of the application varies dramatically, what is of prime importance is a basic understanding of the convection process under reduced gravity conditions. By extending this logic to the rest of the application issues one can arrive at a reasonably self-contained set of research topics or areas of fundamental understanding. These topics/areas include:

- FIRST AND SECOND ORDER PHASE TRANSITIONS
- MULTICOMPONENT/COUPLED TRANSPORT FLOWS
- MAGNETO/ELECTROHYDRODYNAMICS
- MULTIPHASE FLOW
- CAPILLARY PHENOMENA
- NUCLEATION AND CLUSTER PHENOMENA
- ELECTRO-KINETICS AND ELECTRO-CHEMISTRY
- DYNAMICS OF SOLID-FLUID INTERFACES

Obviously there will always be some unique issues in certain applications which do not conveniently fit into the above topics/areas. But, if necessary, they can be addressed on an individual basis. Therefore, it is felt that maximum value to all of the reduced gravity fluids applications can be achieved by maintaining a balanced basic and applied research program across all of the areas/topics.

The program of current and planned activities within the Fluids Discipline attempts to follow this balanced area/topic approach. While the current program is limited in scope and gaps exist, hopefully, as the program grows, the desired balance will be achieved. The current program is divided into ground-based efforts and space-based efforts where a set of space experiments either now exists or are under development. A representative sample of the ground-based activities includes the following topics:

- TRANSPORT PROCESSES IN SOLUTION CRYSTAL GROWTH
- SUPPRESSION OF MARANGONI CONVECTION
- TRANSIENT HEAT TRANSFER STUDIES
- NUCLEATE POOL BOILING
- ELECTRODYNAMICALLY DRIVEN FLOWS IN MOLTEN SALTS
- THERMODIFFUSOCAPILLARY TRANSPORT
- CONVECTIVE FLOW BOILING
- CRITICAL POINT VISCOSITY MEASUREMENTS
- MASS TRANSPORT BETWEEN BUBBLES AND DISSOLVED GASES
- THE CORRELATION LENGTH OF HELIUM II
- ELECTROHYDRODYNAMICS
- FREE SURFACE PHENOMENA
- BENARD STABILITY
- CRITICAL TRANSPORT PROPERTIES OF LIQUID HELIUM

The stable of flight hardware which is avilable or under development for actual space experiments is much more limited including only the following:

- o DROP DYNAMICS MODULE
- o FLUIDS EXPERIMENTS SYSTEM
- o CRITICAL FLUID LIGHT SCATTERING EXPERIMENT
- o SURFACE TENSION DRIVEN CONVECTION EXPERIMENT
- o LAMBDA POINT EXPERIMENT

There are also other sets of complementary experiment hardware which have been developed specifically for the other microgravity science disciplines (e.g., materials processing) which have some limited capability for fluids related experiments. However, even with the potential availability of this complementary hardware, the ensemble of space hardware for fluids experiments is severely limited and inadequate for the desired balanced program of low gravity fluids research. Fortunately, in several of the ground-based efforts, the conceptual designs of space experiments are nearing completion. It is anticipated that these concepts will be developed into actual space experiment hardware in a timely manner to provide a critically needed capability for acquiring low gravity data. There is also a renewed emphasis of more fully exploiting the limited capabilities of low gravity ground-based facilities (e.g., drop towers and aircraft) to also obtain the maximum reduced gravity data they can provide.

## Temperature Measurement Requirements

As mentioned previously, the temperature of the fluid, which may be a liquid or a gas, is a dominant driving or controlling parameter in many of the processes/ phenomena of interest to the Fluids Discipline researchers. In experiments dealing with first order phase transitions such as boiling, condensation, or solidification, the importance of both the local and bulk fluid temperatures are obvious. Likewise, with studies of second order phase transitions such as critical point phenomena it is the precise control and measurement of the bulk fluid temperature that are primary experiment concerns.

In many of the other Fluids Discipline areas/topics the importance of fluid temperature is perhaps less understood than in the above examples. Unfortunately, it is impossible in this paper to elucidate the significance of temperature in all fluids processes/phenomena of interest. However, some discussion on the effects of temperature variations on surface tension forces and their effects on low gravity fluid behavior does seem appropriate. As buoyancy induced flows are diminished as gravity forces are reduced, the relative importance of flows driven by gradients of surface tension become greatly amplified. The surface tension gradients can arise from a gradient of solute concentration but are more commonly the result of a thermal gradient across the surface between two fluids or two phases of the same fluid. Both cellular motion and general convective motion of the fluid can be generated. An increased understanding of the extent and magnitude of these "thermocapillary" flows, whether transient or steady-state, and their stability characteristics are of pre-emptive importance to low gravity fluids research and the applications which that research supports. Hence, in any reduced gravity experiment where thermocapillary flow is studied or may be encountered, the control and measurement of temperature is again a primary concern.

As was mentioned before, the actual fluid temperatures in reduced gravity experiments may range from -271$^{o}$C (i.e., the Lambda point of Helium) to greater than 1000$^{o}$C (i.e., in liquid metals and eutectic salts.). The required control/measurement accuracies of these temperatures may be on the order of microdegrees. In some cases, spatially defined true surface (i.e., in the surface microlayer) temperature measurements are required across the extent of the surface and in other cases accurately defined point measurements within the bulk fluid are required. Obviously, this range of conditions presents formidable temperature measurement challenges.

Fortunately, just as the large number of applications specific fluids issues were reduced to a much more wieldy set of research areas/topics, the range of temperature measurement conditions and requirements can be reduced to a more tractable array for much of the low gravity fluids research within this discipline. The most common fluid temperatures encountered are from 0$^{o}$ to 100$^{o}$C with required accuracies in the .001$^{o}$ to the 1$^{o}$ range. Also, in many instances, standard contacting temperature measurement devices such as thermocouples or thermistors provide adequate results. However, a large number of experiments remain where nonintrusive temperature measurements are required. When the fluid processes/phenomena of interest are near the stability limits or when delicate flow pattern characterization is the core of the experiment, nonintrusive or, at a minimum, noncontact temperature measurement techniques are essential. Also, in some low gravity fluids experiments, a requirement for noncontact techniques is encountered which is not typical in terrestrial laboratories. This requirement involves containerless experiments. The major attribute of these experiments is the capability to float the fluid sample free of any of the contaminating or perturbing effects of a confining and contacting container. Obvious the use of contacting temperature measurement devices would defeat the purpose of a containerless experiment.

## Noncontact Techniques

For many years, a number of noncontact temperature measurement techniques have been successfully exploited in ground-based fluids experiments. More recently efforts have been made to apply these techniques to low gravity experiments. An example of one such successful effort is the holographic interferometry subsystem of the Fluids Experiment System which was flown on Spacelab 3.

In discussing noncontact temperature measurement techniques, it is helpful to separate them into two categories: 1)those appropriate for surface temperature measurements and 2) those appropriate for measurements at sites within the bulk fluid.

The most common techniques for surface fluid temperature measurements involve the application of passive radiometry and/or pyrometry. Other techniques involve active light scattering and/or reflectivity. Most of these techniques are discussed in detail in the other papers at the Workshop and therefore these will not be discussed here. The only comment which must be made about these techniques as they apply specifically to fluids experiments involves the range of fluids of interest and their optical characteristics. Since, in many cases, the temperature of the actual surface is the parameter of importance, special consideration must be given to the transmission and emissivity properties of the fluid. This can make the choice of the spectral wavelength and bandwidth of the measurement system a difficult problem.

For the category of interior site measurements, the list of potential techniques which are available is already quite long but continues to grow as research advances are made. Perhaps the propensity for research directd at improving these techniques for this is due to the fact that in general the existing capabilities of such techniques are still considered too limited or inadequate for many fluids experiments. A particular problem in acquiring accurate data from the interior of the fluid is caused by the fact that the measurement must be made through a pathlength of fluid which is generally of an unknown or varying character. A general classification of the most promising techniques can be made in terms of: 1) index of refraction methods and 2) spectroscopic methods. Only a limited discussion of these techniques will be attempted.

Index of Refraction Method - These techniques rely on an interpretation of variations in the measured index of refraction and its known constituative relationships to temperature. Such constituative relationships are the Lorentz-Lorenz law for liquids and the Gladstone-Dale relation for gases. Techniques based on interferometry, either classical Mach-Zehnder interferometry or holographic interferometry, directly measure the index of refraction. Techniques based on deflectometry, such as those using schlieren or moire' fringe data, provide measurements of the gradient of the index of refraction which must be integrated to infer temperature. In those cases where the directionality of the gradient field is not known a priori, using deflectometry generally requires multiple measurements or complementary techniques to resolve the various components.

When applying any of the index of refraction methods the additional functional dependence of the index of refraction on concentration/density must be taken into consideration. In the simplest cases, the concentration field may be assumed to be sufficiently constant to allow accurate temperature interpretations. In other cases, additional measurement information must be obtained. One technique to supply this needed information when using interferometry is to collect the data at two or more optical wavelengths.

Spectroscopic Methods - These techniques generally rely on a determination of Boltzmann distribution of the molecular state populations of the fluid at the measurement site. The data necessary for the determination may be acquired through a variety of light scattering, fluoresence, or absorption technqiues. Because of the large number of technqiques that have been developed or are under development (e.g., spontaneous and stimulated Raman scattering incuding coherent anti-stokes Raman, Rayleight scattering, laser induced fluorescence, etc.), any attempts at discussing them in this paper would be totally inadequate. There are volumes of technical reports and books which discuss each of these separate techniques in detail. A common factor in most of the techniques is that lasers are used as a light source to supply needed energy fluxes and spatial resolution.

## Concluding Remarks

In the above discussions of measurement requirements and techniques, an elaboration of the peculiar requirements of reduced gravity experiments has generally been omitted. This was done because, in reality, the measurement requirements for such experiments and the techniques like to be employed in them are equally applicable to the much larger field of terrestrial fluids research. There are many efforts currently devoted to the refinement of current techniques and the development of new techniques with significant advances rapidly emerging. The challenge presented to the reduced gravity fluids researchers and experiment developers is to expoit and adopt those techniques which can best satisfy their measurement requirements within the unique environment of a microgravity laboratory. Whether that laboratory is ground-based, such as in drop towers or aircraft, or space-based, such as in the Shuttle or the Space Station, the constraints of limited power, weight, and volume, the imposition of high shock loads, and the necessity for reliability and operational simplicity must be accommodated. Until this challenge is met, the future contributions of reduced gravity fluids research will be impaired.