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CRYOGENIC FLUID MANAGEMENT IN SPACE

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ABSTRACT

Many future space based vehicles and satellites will require on orbit refuelling proceedure. Cryogenic fluid management technology is being developed to asess the requirements of such proceedure as well as to aid in the design and development of these vehicles. Cryogenic fluid management technology for this application could be divided into two areas of study, one is concerned with fluid transfer process and the other with cryogenic liquid storage. This division is based upon the needed technology for the development of each area. In the first, the interaction of fluid dynamics with thermodynamics is essential, while in the second only thermodynamic analyses are sufficient to define the problem. In this report we discuss the following specific processes related to the liquid transfer area: tank chilldown and fill; tank pressurization; liquid positioning; and slosh dynamics and control. These specific issues are discussed in relation with the required technolgy for their development in the low gravity application area. In each process the relevant physics controlling the technology is identified and methods for resolving some of the basic questions are discussed.

INTRODUCTION

Satellites, orbital vehicles, and manned space stations may remain in space permanently in the future. Among the missions planned are the Space-based Transfer Vehicles (STVs), the Space Station, the long life version of the Shuttle Infrared Telescope Facility (SIRTF), the Large Deployable Reflector (LDR), and the Gravity Probe B (GPB) to name a few. All of these missions require cryogenic liquids for fuel or coolant which must be replenished on orbit periodically from tankers which are stationed in orbit. Cryogenic fluid management has become an important componenet of the design and development of these future vehicles. Thus cryogen transfer and the long term storage of cryogens will be required as an enabling technology for future space missions.

Cryogen fluid management studies began with the advent of the space program due to the use of liquid hydrogen and oxygen for fuel. More than two decades ago a need by NASA developed for controlling propellant position in low-gravity environment with regards to its Apollo program. The Saturn V/S-IVB stage had to be restarted in Earth's orbit after coasting for an extended period in order to place the Apollo in a translunar trajectory. For this end several studies on liquid orientation and cryogen storage in low gravity environment were conducted culminating in an on orbit experiment to gather the necessary data required for the design of the vehicle (Swalley et al., 1966). This was part of an ongoing extensive program to study the effects of low gravity on cryogenic fluid behavior and storage which gave rise to a wide ranging research effort(see for instance Abramson 1966). Needless to say that a vehicle was successfully designed and flown.

With the subsequent advent of the Shuttle program attention was focused more on the storage and the transfer of large amounts of cryogens in terrestrial environment. This was needed to supply the external tank with the necessary liquid fuel. With this program the emphasis was shifted to cryogen management of large quantities without particular attenttion on cryogen losses and problems concerned with low gravity liquid positioning. However, the low gravity cryogen cooling program necessary for the various satellite operations continued to push the small scale cryogen management technology development by

NASA.

Research on low-gravity cryogenic fluid management continues to be persued by NASA as part of the ongoing space program. Specifically, two programs dealing with low gravity cryogenic fluid management are being persued simultaneously, one is directed towards cryogenic cooling applications while the other dealing with the basic scientific questions connected with liquid fuel managenet applications. Cryogenic cooling was found to be necessary in a veraity of space instruments in which NASA continues to play a leading role in developing (see for instance Sherman 1982). On the other hand, there remained unresolved many basic scientific questions with regards to the role of gravity in two-phase flow and heat transfer at cryogenic temperatures. For this objective selected problems dealing with fundamental issues for which it was thought more research was needed were identified and subjected to intensive examination. Major among these issues is liquid slosh in various tank geometries, tank chilldown and fill, and long term cryogen storage. In all of these issues two-phase flows and heat transfer appear to be very important. A major componenet of this effort is a planned space flight experiment to gather the urgently needed data for that specific technology area (Aydelott 1985). Basically, the experiment consisted of two tanks connected by a transfer line to be placed in the Shuttle cargo bay and in which the working fluid was a cryogen. Several specific issues are to be investigated among which is the recieving tank chilldown and fill, transfer line chilldown, liquid acquisition devices performance and tank pressurization. Recently this experiment has been upgraded into a stand alone space flight experiment in which the working fluid is liquid hydrogen (LH2). However, the technical issues to be investigated remained the same (see Aydelott and Devol, 1987).

The objective of this report is to study four of the major technical issues relevant to low gravity cryogen liquid management and to provide a timely assesement of the present technology status of these issues. Specifically, the issues in question are: tank chilldown and no-vent fill, pressurization system performance, liquid reorientation, and slosh dynamics and control. This study was conducted with application to the Space-based Transpt Vehicle liquid propellant on orbit refill in mind.

DISCUSSION

As discussed in the introduction the on-orbit STV refuelling process is an important componenet of the function of the vehicle. This process requires a thorough understanding of the various aspects of cryogen liquid transfer and storage in space. Cryogen liquid transfer process involves several tasks some of which are: transfer line chilldown, recieving tank chilldown and fill, liquid orientation, and storage vessel drainage. While cryogen storage process is primarily concerned with: pressure control, insulation, and slosh control. Of the tasks enumerated above it was decided to concentrate on the foilowing:

tank chilldown and no-vent fill,

pressurization system performance,

liquid reorientation, and

slosh dynamics and control.

These isuues will be discussed in this section with respect to the important physical processes involved in each and the state of the art level of understanding of the physics of each process. With the understanding that the interest in here is in the STV design, the impact of low gravity environment on these issues must be considered. This requires an assesement of low-gravity testing as well as terrestrial testing.

1. Tank Chilldown and No-Vent Fill

Tank Chill down and fill constitutes a crucial step in any refuelling process since this process will be repeated every time a refill of the STV is accomplished. This process will involve initially of lowering the wall temperature of the empty recieving tank from ambient to a temperature close to the liquid temperature. This is basically accomplished through the introduction of a small charge of liquid into the tank either through a spray or a jet which should contact the tank wall. In this instance heat is rejected from the wall through conduction and is absorbed by the liquid in the form of latent heat of vaporization. This process is repeated untill the tank wall reaches the desired temperature. However, due to the liquid evaporation mechanism the tank pressure will rise.

The amount of coolant needed to lower the tank temperature from its ambient value

to a final value can be easily calculated through a thermal balance analysis if the thermodynamic properties of both the coolant and the tank material are known. However, the time needed to accomplish this task is not as easily calculable. The cooling rate is a strong function of the cooling technique employed. The method for calculating this rate varies according to whether a jet is used or a spray. In both cases, however, the cooling rate is predicted by analyzing the hydrodynamic behavior of the cold liquid upon impingement on a hot surface. As an example, the cooling rate will be different for a cold drop impacting a hot surface and for a liquid film moving on a surface. For both cases realistic hydrodynamic-thermal models can be constructed to predict cooling rates once the fluid behavior at and during impact is known. Fluid behavior upon impact can be calssified through experimental means. For a drop for instance, it is well known that its shape evolution, and hence the heat transfer rate, when it impacts a hot plate is a function of the Weber number (Bolle and Moureau 1982). The Weber number is the ratio of the drop's kinetic energy to its surfac energy due to surface tension. In order to determine the cooling rate it is possible to use the extensive amount of research that already exists for both spray cooling and liquid jet cooling. An excellent review of this subject is given by Bolle and Moureau (1982).

Of course all of the work performed to date on spray and jet cooling has been for terrestrial conditions. It is hard to believe that the hydrodynamics and thermodynamics of this problem is substantially affected by gravity. One area where gravity influence may be felt is in the maximum drop size that can be obtained under low-gravity conditions. It is possible to imagine that drop morphology upon impact will be different for larger drops. However, this problem can be supressed by imposing a maximum allowable drop size.

There are two deficiency areas in our knowledge that can be immediatly identified. One is whether liquid drops disintegration upon impingement on a wall at cryogenic temperatures does obey the established Weber number classification for water? The second is whether this classification is also valid for low-gravity impact environment. Both of these questions can be easily answered with a few simple experiments using either drop towers or parabolic trajectory airplane flights.

Once the tank wall temperature has reached the desired value the filling process of the tank may commence. It is known that the initial amounts of the incoming liquid may vaporize upon entering the tank which will cause the pressure inside the tank to rise. Due to imposed structural constraints the tank pressure can not be allowed to exceed a set value. Thus the tank pressure must be lowered. For the low gravity fill applications it is desireable to achieve the low pressure without venting any of the cryogn. This last condition is imposed to save as much of the fuel as possible since fuel losses cannot be tolerated. The obvious way to achieve no vent fill is to allow the gas inside the tank to condense by further reduction of the tank temperature. It is possible to calculate the liquid mass and degree of supercooling needed to achieve a specific percentage of tank fill under the maximum allowable pressure constraint.

The pressure rise inside tanks of simple geometries (cylindrical, spherical etc.) during a no vent fill process can be readily calculated from the hydrodynamic-thermodynamic governing equations. The solution to these equations may be obtained using computational fluid dynamics (CFD) techniques. In addition to the transient pressure history the temperature of both the fluid and the tank wall and other related field variables could be calculated through these means. Earlier attempts to obtain such solutions via CFD techniques were undertaken by Barakat et al. (1966) and Merte et al. (1970). However, CFD has advanced tremendously in the past 20 years permitting realistic and meaningfull solutions to be obtained for the no vent fill process without much trouble.

Basically, the no vent fill process can be modeled by the incompressible mass, momentum and energy conservation equations for the liquid segment and their compressible counterpart for the gas space. Vaporiztion and condensation on both the solid-gas and liquid-gas interfaces can be accounted for through balances of mass and energy across these interfaces. Also, the liquid influx into the tank can be handled through appropriate boundary conditions. The only problem with this analysis for in gravity applications is the initial position of the liquid-gas interface. In terrestrial environment the interface equilibrium position in a motionless liquid can be assumed to be flat in a plane normal to the gravity vector. However, in zero- or low- gravity environment the gas-liquid interface

is dominated by the surface tension force which is a function of temperature. It can be shown (Reynolds and Satterlee, 1966) that the hydrostatic, stable, equilibrium liquid-gas interface position in an isothermal zero-g environment is one in which the total potential energy is minimized. Thus it is obvious that for an environment such as the no vent fill which is not isothermal an assumption on the initial position of the interface is no trivial matter. Under hydrostatic conditions, the minimization of the surface energy problem reduces to a purely geometric problem. Some calculations have been performed for stable meniscii shapes in spherical tanks under zero-g conditions. However, we can not find any evidence of experimental attempts to verify these calculations.

It is possible to extend the above discussed claculations of Reynolds and Satterlee to the dynamic conditions appropriate to the fill process and thus produce some predictions on shapes and positions of the gas-liquid interface. Once the difficulty connected with the meniscii shapes is resolved then the pressurization problem during no-vent fill may handeled convienently.

The important physical processes involved in the tank chilldown and fill is clearly the coupling between fluid dynamics and thermodynamics as it relates to cold drop impact on a warm surface and the initial position of the liquid gas interface. We need to understand the drop impact mechanism as well as the flow of liquid in a tank in low gravity. Some low g tests are needed for the drop impact problem but none is needed for the no vent fill problem. Clearly for the drop impact problem the Weber number is important while for the no vent fill is the Reynolds number as well as the Bond number are important. The drop impact experiment should be performed with a cryogen liquid in order to fully evaluate the effects of large temperature gradients on this problem. It is immaterial what liquid to use.

2. Pressurization System Performance

The problem of moving the liquid fuel from the storage tank to the recieving tank can be considered as a complimentary problem to the tank fill process. This problem arises whenever a STV fuel tank is needed to be filled on orbit. This process is also of

some concern in cryogenic engineering under terrestrial environment. Under terrestrial conditions Barron (1985) cites three methods that are commonly used to drain cryogenic liquids from the storage vessel. These methods are: (1) self pressurization, (2) external gas pressurization, or (3) pump transfer. It is natural to assume that these same methods are utilized in low gravity applications. The consensus among the low gravity fluid management community has been to employ the pressurization technique, whether self or external, for the on orbit liquid drainage process (see Aydelott and Devol, 1988). Pressurization method of drainage involves creating the pressure differntial needed to expel the liquid by injecting gas in the ullage space to increase the gas pressure. In self pressurization, the gas injected is the same as the ullage gas while external pressurization involves introducing high pressure gas from an external source.

From the fluid-thermodynamic point of view the prssurization and the no vent fill processes are analogous with probably the only difference between the two being the tank size. It is possible, then, with simple thermodynamic analyses to calculate the amount of pressurant gas required to induce a specific mass flow rate using heat and mass balances. Such calculation in which the saturation rule is used may be found in Epstein (1965). This technique is known as the lumped system method for calculating pressurization requirements in which only the mean properties of the gas space and tank wall are determined (Barron 1985). However, when more details on the pressurization process are required such as the temperature, composition, velocity or pressure as functions of both space and time, then a distributed analysis is necessary. Such requirement arises whenever a specific control of the process is contemplated. For the distributed analysis again the governing conservation equations of mass, momentum and energy must be solved in both the liquid and the gas. Clark (1965) gives a very good review of the then state of the art for such calculations in terrestrial environment. The similarity between the fill and pressurization processes for the distributed system is obvious in that the necessary calculations are basically CFD calculations which has advanced significantly in the past twenty years.

It is possible to simulate the pressurization and drainage process numerically, provided the initial position of the liquid surface is known and the pressurant gas speed is modest.

The CFD models envisioned for use in these analyses must account for condensation and evaporation across the interface and along the gas-solid boundaries. CFD models can then predict with reasonable accuracy the pressure history and other field variables as well as the position of the liquid in the tank. However, this solution will be appropriate to the specific initial conditions imposed. It is these initial conditions that need to be determined with some confidence.

Again, as in the no vent fill case, in the pressurization process the liquid-gas interface position and shape appear to be an obvious place where gravity may play a role. Thus an analytical model which could predict the interface characteristics in low gravity is essential for disributed system analysis. However, the problem here is not as critical as in the no vent fill process. The position of the inlet nozzle for the pressurant may be open to either the gas or the liquid without affecting the pressurization process itself. On the other hand, the position of the liquid outlet nozzle is very critical in order to allow only liquid to be expelled. Thus it is imperative in this case to be able to predict the liquid position in the storage tank during draining. It is well known from previous work (e.g. Reynolds and Satterlee, 1965) that wetting liquids tend to wet more under low gravity conditions. Hence it is safe to assume that a nozzle placed flush with the tank wall will only allow liquid to be expelled if the gas pressure is not too great so as to break up the liquid surface.

The pressurization process appears to be amenable to moderate CFD modelling effort which needs to be formulated specifically for the liquid expulsion task. However, substantial amount of analytical modelling need to performed in order to accuratly predict the initial conditions, specifically, the liquid surface initial position. The analytical modelling effort must be augmented with simple ground based as well as flight experiments. The effort in this task should be directed towards understanding of the role of surface tension forces, in the absence of the gravity force, in defining the liquid-gas interface.

The pressurization system performance is dependent upon the interaction of thermodynamics with fuid dynamics. This whole technology area can be realistically modeled via CFD analysis. The most important parmeter in this problem is the Bond number. It does not appear that a filght experiment is necessary in order to predict the pressurization

process or pressure collapse.

3. Liquid Orientation and Slosh Dynamics and Control

The technical issues related to liquid orientation in low gravity and slosh dynamics are closely related in the sense that both processes are primarily concered with only fluid dynamics with minimum thermodynamic effects. Consequently, these two isuues will be discussed together in here. Of all the technical issues involved in the cryogenic fluid management technology the problem of slosh dynamics and control has recieved the greatest amount of attention over the years. For this reason there exists a substantial amount of information, both analytical and experimental dealing the low gravity aspects of this problem. The problem of slosh dynamics is of direct importance to space technology especially for liquid propulsion launch vehicles. Such devices have an enormous percentage of their initial weight as fuel and consequently the dynamic forces resulting from the motions of these large liquid masses could be very substantial even beyond the capabilities of the control system to counteract them or the structure to resist them. If the dominant fuel slosh frequencies are close to any of the control system frequencies, an instability of the flight characteristics can result; while if the slosh frequencies are close to the elastic body bending ferquencies a large amplitude dynamic response problem may arise.

Due to the criticality of this issue to the launch vehicle design and performance and hence to the space program in general a great amount of research has been devoted specifically to study the problem of slosh dynamics. A review of the available literature at that time is given in Abramson (1965). However, due to the fact that the launch vehicles dispose of most of their fuel in the very first few minutes of launch, the influence of low gravity on this problem was not of primary concern in that body of research. With the subsequent prolific use of satellites and also the expansion of the space program to interplanetary flight a need developed for understanding slosh dynamics and control in low gravity environment. This need resulted in a substantial amount of research which is documented in various books and monographs the most recent and comprehensive of which is given in the book by Myshkis et al. (1987).

Since the original primary goal of the study of slosh dynamics was concerned with the identification of the slosh frequencies for various tank geometries, vibrational environment and fluid fill configurations the problem was resolved through analytical models. In order to solve these models in a straight forward manner specific attention was paid to the linearized form of these models. The linearized system can readily identify the various slosh frequencies without resolving the interaction problem. For the resolution of that latter problem one must turn to the nonlinear form of the models or nowadays to CFD techniques. The only difficulty with the linearized models is the tank shape (i.e. spherical, cylindrical etc.). The more complex the tank geometry is the greater the amount of work needed to determine the slosh frequencies.

The general model for the slosh dynamics problem as well as the fluid orientation problem is constructed by assuming the liquid in the container to be inviscid, irrotational, and incompressible whose velocity field u_i is given by $u_i = u_i(x_i, t)$. This velocity field is governed by the equations of motion given by:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_i} = -\frac{1}{\rho} \nabla p - \nabla \Pi, \tag{1}$$

where $p = p(x_i, t)$ is the pressure field in the liquid and Π is the potential function for the body force including gravity. Since the fluid is assumed to be ideal then the velocity field is describable by the potential function, Φ:

$$u_i(x_i, t) = -\nabla \Phi(x_i, t). \tag{2}$$

Which with the conservation of mass equation leads to Laplace's equation for Φ:

$$\nabla^2 \Phi = 0 \tag{3}$$

. The shape of the liquid gas interface must satisfy Laplace's condition on the pressure drop across the interface given by:

$$p_o - p = \sigma(k_1 + k_2), \tag{4}$$

where $p_o = $ const. is the pressure of the gas, while k_1 and k_2 are the principal normal sections of the interface. σ is the surface tension. The model for slosh dynamics must also

satisfy the Dupre-Young condition on the contact line at the triple contact point of the liquid, gas and solid given by:

$$\sigma(cos\alpha) = \sigma - \sigma_o, \tag{5}$$

where α is the contact angle of the liquid.

In this model for the slosh problem the gas pressure p_o is assumed to be constant and known throughout the gas space and hence no equations are needed for its description. To complete the problem the the usual inviscid solid-liquid boundary conditions:

$$u_n = -\partial\Phi/\partial n = 0 \tag{6}$$

must be satisfied on all solid walls. n is the unit outward normal. Also on the liquid-gas interface the condition that the rate of displacement of the interface is equal to the velocity component normal to the interface is imposed:

$$\partial\Phi/\partial n = -\partial N/\partial t, \tag{7}$$

where $N(x_1, x_2, t)$ is function describing the gas liquid interface. Note, since the thermodynamic effects are neglected for this problem, no condensation or evaporation is allowed to take place across the interface.

It should be observed that the governing field equation is linear, in this case it is Laplace's equation, Eq. (3) above. The nonlinearity of the problem in this model is in Laplace's condition, Eq. (4) which describes the interface curvature. The linearized slosh dynamics problem is obtained from the linearization of this condition. The linearized problem is normally cast in the form of an eigenvalue problem in which the eigenvalues determine the slosh frequencies. These frequencies are the slosh frequencies appropriate to the specific tank shape and liquid fill level. These frequancies have been identified for various simple tank shapes. Such an eigenvalue solution is normally considered an analytical solution even though in some cases it requires a moderate amount of numerics.

When condition (4) is not linearized then the problem can not be described as an eigenvalue problem and a more complicated proceedure for the solution of the problem

must be adopted. There are basically two ways of solving such nonlinear problems, one is is through numerical approximation of the solution and the other through an eigenfunction expansion in terms of the eigenfunctions of the linearized problem. The first method is basically a CFD technique which is fairly common nowadays. In fact there exists a numerical code developed specifically for the slosh dyanmics problem available for use, Torrey et al. (1987).

It is clear from examining the governing equations shown above that gravity plays an important role in this problem. In fact the dominant parameters, besides the liquid and gas properties, as they appear in equations (1) - (7) are: gravity (this is implied in the potential function for the body force, Π), the surface tension, σ and the contact angle, α. Thus any solution, whether linear or nonlinear should be in terms of these parameters. The two forces that dominate this problem are clearly the force of gravity and the capillary force whose ratio is the Bond number. Thus it is appropriate to take the Bond number as the single most important parameter in any numerical or experimantal simulation. It is clear that under low gravity conditions the capillary forces are dominant. Thus any free surface configuration, as well as the dominant frequency can, in principle, be calculated for the appropriate Bond number and imposed vibrational frequency. Once the shape and the dynamics of the free surface is known for a given set of conditions, then the slosh control problem may be tackled depending on the desired requirements.

The liquid orientation problem, since it requires determining the motion of the bulk of fluid subject to a specific force must be handled through CFD techniques. The formulation of the problem is subject to the same governing equations used for the slosh problem in a slightly modified form. Equation (1) may be modified to include viscous effects, in which case the velocity field can not be written in terms of a potential function. However, equations (4) through (7) above for the interface and boundary conditions must hold. Given a specific external force and the initial position of the liquid in the tank then final position of the liquid can be determined using numerical means such as VOF3D code (Torrey at al. 1987). This problem is very similar to the large amplitude and interaction slosh dynamics problem.

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