ESRO SP-101

SOME PHYSICAL AND CHEMICAL PROCESSES IN FLUIDS

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ABSTRACT

The ability to reproduce reduced gravity conditions for long periods is one of the reasons why the orbiting laboratory is so attractive.

In this paper several fluid dynamics problem areas are reviewed in which zero-gravity conditions are of great importance. Although emphasis is placed on space processing, there are some older problems also in which gravity masks the phenomena, impeding a reasonably simple approach to the solution.

Three problems are considered:

Thermal convection under reduced gravity. The damping effect of surface gravity waves at the outset of convection induced by surface tractions is discussed in particular. The existence of convection is of concern for some satellite thermal control techniques presently used, and for most of the proposed manufacturing processes. Whereas convection should be normally avoided, problems related to the containerless stirring of a melt constitute an exception.

Secondly, gravity and chemical reactions. Although chemical reactions are independent of gravity because of the small mass of the molecules and atoms involved, in many cases the reaction rate depends on the arrival of the species to the reaction zone. When the arrival process is buoyancy-controlled, the net speed of the reaction will be affected by the gravity.

Thirdly, two-phase flows under reduced gravity provide interesting problems from boiling heat transfer to degassing of melts. This part of the paper deals only with the measurement of sound velocity in a liquid containing bubbles. It is suggested that such measurements should be made under reduced gravity to provide reliable results.

1. INTRODUCTION

Spacelab, with its unique capabilities of low gravity and ease of access to high-energy radiation and to high vacuum, offers wide-ranging possibilities for performing basic studies in connection with physical and physico-chemical phenomena in fluids, and for developing processes for manufacturing new products in space to be used both on Earth and in space.

Several problems are reviewed for which the reproduction of zero-gravity conditions seems important.

(i) In many cases they belong to a rather antique discipline, which is probably not very fashionable from the point of view of space research, but the phenomena involved are fairly complicated and are masked on Earth by the effects of gravity. One such example may be cavitation, an unpleasant phenomenon whose harmful effects handicap many engineering developments.

(ii) In other cases, mathematical expediency induces us to neglect gravity effects in order to obtain a reasonably simple picture of the phenomenon. The results of the experimentalist conflict with those of the theoretician, and it is not quite clear who is to blame for this discrepancy. A good example is Godsave's model of a single droplet burning in air, which is used extensively in the study of the combustion in gas turbines, jet engines and rocket motors. In the model, free convection effects are neglected, so that the temperature and concentration fields may be assumed to have spherical symmetry. The adequacy of the model is presently well established, thanks to a complete series of experiments performed by Kumagai and co-workers with a free-fall chamber.

(iii) Some of the processes to be discussed are connected with current space techniques. The research on diffusion flames may be pertinent to the study of the inflammability of materials for the space laboratory.

Fluid convection under reduced-gravity conditions should be of particular interest for studying the performance of phase change materials used for spacecraft thermal control. Under heating conditions these materials melt, freezing when the temperature falls again. The convection provides high heat transfer rates that are desirable in most cases, since known phase change materials are fairly poor heat conductors.

(iv) Looking to the near future, the advantages of several of the suggested space manufacturing processes are based on the presence of conditions that are not easily reproducible on Earth. The supposed absence of thermally-induced convection under reduced-gravity conditions is a good example. A fairly large number of recently published papers deal with the nature of convection in low-gravity environments. Many inducing mechanisms have been proposed. Although recent experiments indicate that convective driving forces other than gravity are present in low-gravity environments, very little is known at present about the nature of these phenomena.

(v) Gravity may have important effects in chemical reactions. Although it is fairly well established that chemical reactions in a homogeneous reactor are independent of gravity, because of the small mass of the molecules and atoms involved, in most cases the rate and effectiveness of the chemical reactions are influenced by the availability of the reactants. As the reaction advances, reactants are depleted and must be replenished by some diffusion process. When the species react rapidly once they are mixed, their arrival at the reaction zone is the controlling mechanism. If the diffusion process is induced by buoyancy, as in the ordinary candle, the net attainable speed of the reaction depends on gravity.

In addition, some chemical processes seem better suited for use under reduced-gravity conditions than for use on Earth. The fluidised-bed process is an obvious case. Solid particles may be suspended in a gas or liquid phase, forming a fluidised bed. On Earth, the fluidised particles attain a 'suspended' state when fluid-dynamic drag plus buoyance counterbalance the weight of the particles. Under reduced-gravity conditions, very low fluid velocities are required to suspend the particles; this has the advantage that longer contact times between gaseous reactants and the solid are possible; in addition the danger of nonhomogeneous fluidisation is greatly reduced.

Because of the limited space available here, three main topics will be reviewed:

(a) thermally induced convection under reduced gravity;
(b) burning of a fuel droplet in an oxidised atmosphere;
(c) measurement of sound velocity in a liquid containing bubbles.

2. CONVECTION UNDER REDUCED-GRAVITY CONDITIONS

The possibility of avoiding convection is one of the main reasons for the attractiveness of space processing. At times it will be desirable to keep fluid motion to a minimum or even to eliminate it completely; solidification and crystal-growing are two pertinent examples. At other times, however, it will be desirable to stir the fluid phase quite vigorously for mixing or cooling purposes. The advantages of containerless melting will be useless in some cases unless problems connected with the remote stirring of the melt are solved.

A very complete survey of possible convection-inducing mechanisms has been made by Grodzka[1], while Bourgeois & Brashears[2] have fairly recently discussed the physical forces that could induce fluid flow in some melting experiments performed aboard Skylab during June 1973.

The main convection inducing mechanisms are the following (see summary Table 1).

1. Thermal convection

(a) *Gravity* (buoyancy effects)
The density of the fluid depends on temperature and normally decreases when the temperature increases. This is usually the dominant convection-inducing mechanism under one-g conditions.

(b) *Accelerations and g-jitter*
Varying gravity-levels result in the space laboratory from engine burns, attitude-control manoeuvres, gas venting, and onboard vibrations from machinery or astronaut movements. It should be pointed out that once some stratification is produced by a temperature or concentration gradient, the resulting fluid configuration is extremely sensitive to accelerations acting normal to the density gradient, so that some degree of convection is unavoidable even in low-gravity environments. If a steady low-gravity acceleration parallel to the density gradient is superimposed, it will have either a damping or a magnifying effect on the instability, depending on whether the acceleration and increasing density are in the same or in opposite directions.

(c) *Surface tension and interfacial tensions* (Marangoni convection)
These tensions appear in liquid-gas or miscible liquid-liquid interfaces. The surface tension varies with temperature, generally decreasing when the temperature increases. Surface tension gradients induce surface tractions. This mechanism is dominant under normal gravity conditions only if the fluid-layer thickness is small enough. In space, it is nearly always dominant if an interface exists.

(d) *Thermal volume expansions* (thermoacoustical convection)
When a fluid being heated from a wall expands, the whole mass of the surrounding fluid is set into slow motion provided that the heating rate is not high (bulk motion). On the other hand, if the heating is rapid, compression waves appear which under some circumstances may be amplified. The latter is the mechanism of disturbance of an air stream by a flame, which is well known to propulsion specialists, but it is not very likely to be present in a small container in space, except when conditions (heating process, container shape...) are appropriate for inducing resonance phenomena.

2. Concentration or solutal convection

(a) *Gravity, accelerations and g-jitter*
The same as in 1a and b, except that in this case the density gradients are due to the concentration of chemical species.

(b) *Surface tension forces*
Surface tension is extremely sensitive to minute gradients in the chemical composition of the fluid. Once surface tension gradients appear, the onset of the convection process is the same as in 1c.

(c) *Thermal diffusion* (Soret effect)
When thermal diffusivity is greater than concentration diffusivity, heavier components will migrate toward the colder region, against the concentration gradient. This mechanism has been the subject of particular interest recently because of possible space applications. On Earth it has been demonstrated for the last thirty years, and has been applied commercially in at least one device, the iodine lamp[3].
Thermal transpiration - the flow of gases through porous membranes, at low pressures, under the action of a temperature gradient - may be considered as a particular case of thermal diffusion since the membrane may be viewed as an ensemble of motionless macromolecules[4].

Table 1. Main convection-inducing mechanisms

SOURCE	INDUCING MECHANISM	PHYSICAL MAGNITUDES INVOLVED	OBSERVATIONS
1 Thermal convection	(a) Gravity	Temperature-density-buoyancy	Usually dominant under 1-g
	(b) Accelerations and g-jitter	Temperature-density-body forces	Probably important under 0-g
	(c) Surface tractions	Temperature-surface tension	An interface must be present
	(d) Thermal volume expansions	Temperature-density-pressure	Small except under fairly particular circumstances
2 Concentration or solutal convection	(a) Gravity, accelerations, g-jitter	Concentration-density-body forces	As in 1a and b, but the density gradients arise because of concentration gradients
	(b) Surface tractions	Concentration-surface tension	Same as in 1c. Surface tension is very sensitive to concentration
	(c) Thermal diffusion (Soret effect)	Temperature-concentration-thermal diffusion ratio	Heavier components migrate towards the colder regions
	(d) Diffusion stresses	Concentration-diffusion velocity	Momentum transfer because of diffusion velocities
3 Electric and magnetic convection	(a) Electroconvection	Temperature-electric conductivity-applied DC electric field-body forces	Poorly conducting fluids
	(b) Electrostriction	Density-dielectric constant-applied DC electric field-body forces	Poorly conducting fluids
	(c) Magnetoconvection	Temperature-electric current-applied magnetic field-body forces	Conducting fluids. Current generated by Thompson effect interacts with the applied magnetic field
		Temperature-magnetic susceptibility-non uniform magnetic field-body forces	Non-conducting but paramagnetic fluids
	(d) Magnetostriction	Density-magnetic permeability-applied and induced magnetic field-body forces	Magnetic fluids
4 Phase-change-induced convection	(a) Shrinkage forces	Liquid-solid densities	Interface acts as a liquid sink
	(b) Vapour pressure	Molecular forces	Evaporating molecules transfer momentum to the interface
	(c) Boiling	Dynamic forces	Agitation produced by bubbles growing and collapsing
5 Others	(a) Coriolis forces	Temperature (concentration)-density-body forces	Included in 1b and 2a
	(b) Jet effects	Dynamic forces	Because of melting beam, aerodynamic support of the melt,...

(d) *Diffusion stresses*
It has been shown that diffusion velocities, due mainly to concentration gradients, transfer momentum throughout the different fluid layers, giving rise to a diffusion stress tensor. This effect is normally of second order compared with the ordinary viscous stress, except in gases under rarefied conditions.

3. Electric and magnetic convection

Magnetic and (or) electric fields may be introduced on purpose to stir the melt, or through the melting process, as when an electron beam is used. Under such conditions motion may be induced by the following mechanisms:

(a) *Electroconvection*
The natural electrical conductivity of poorly conducting fluids is temperature-dependent, so that a gradient of charge density within the fluid appears as a consequence of an existing thermal gradient. Once a DC electric field is applied, convection may appear.

(b) *Electrostriction*
In the case of a poorly conducting fluid, the electrical permittivity (dielectric constant), although a fairly weak function of temperature, depends on density. If the fluid is stratified, an applied electric field will induce different electric flux densities in different layers, thereby promoting instability.

(c) *Magnetoconvection*
In an electrically conducting fluid, a thermal gradient generates an electric current (Thompson effect) which interacts with an applied magnetic field to generate an induced Lorentz force, which causes fluid motion.
For nonconducting but paramagnetic fluids, the magnetic susceptibility depends on temperature. Since the magnetic force per unit volume in an insulating fluid is equal to half the volume susceptibility multiplied by the gradient of the squared modulus of the magnetic field, a stratified body force will appear in the presence of a thermal gradient and a magnetic field gradient.

(d) *Magnetostriction*
The magnetic permeability is density dependent. If a given magnetic field is applied to a magnetic fluid, the induced magnetic field will depend on density, so that a stratified body force will again appear.

4. Phase-change-induced convection

(a) *Shrinkage forces*
Density differences accompanying solidification cause flow inward to an advancing solidification interface.

(b) *Vapour pressure*
Evaporating molecules transfer momentum to the liquid vapour interface. On the other hand, once depleted, the vaporising material must be replenished, which could induce preferential mass transport in the liquid phase to spots undergoing nonuniform vaporisation.

(c) *Boiling*
When a liquid pool boils, liquid motion is induced not only by free convection currents, but also by additional agitation because of the bubbles growing and collapsing.
In addition, different inducing mechanisms would appear because of peculiarities associated with the experimental set-up: centrifugal and Coriolis forces if some turning mechanism is used to hold the samples to be melted, jet or beam effects of the melting beam, and so on.

2.1 THERMALLY-INDUCED CONVECTION IN ENCLOSED LIQUIDS OR GASES

Some experiments on natural convection in low-gravity environments, conducted during the Apollo-14, 16 and 17 and Skylab space missions, have been reviewed fairly recently by Grodzka & Bannister[5].

The convection experiments aboard Apollo-14 gave a clear indication of the existence of convection in confined gases or liquids. Temperature changes followed by means of liquid crystal indicators showed that heat transfer rates were larger than those calculated assuming conduction and radiation only. This puzzling result was tentatively explained by either:

(a) the existence of an 'intrafacial tension' owing to large differences in physical properties between two adjacent liquid layers[6]. These differences are due to the large temperature gradients existing when heat is transferred by conduction alone, as is the case at the outset of the experiment;
(b) thermal volume expansion, as indicated in 1d[1], or

(c) g-jitter effects, as already mentioned in 1b[5]. It now appears that g-jitter was an important convection-triggering mechanism in the Apollo-14 experiment.

Clearly much more work will be devoted to detecting the onset of thermal convection in confined liquids and gases under reduced-gravity conditions, but acceleration as well as heat-transfer data would be required.

Probably, the measurement of fluid velocities (instead of heat transfer plus accelerations) should be a more direct and convenient approach. It has been suggested that an array of hot-wire probes immersed in the fluid will be used to detect the onset and evolution of convection[7]. Hot-wire anemometry involves some drawbacks when used to measure slow fluid motions because the hot-wire near field may be affected by the free convection that the wire produces in the fluid. In addition, some wire degradation effects are expected with most liquids. Once several fairly delicate calibration problems have been solved, hot-wire anemometry seems to be well suited for detecting very low convection velocities.

2.2 MARANGONI CONVECTION

The convection induced by interfacial forces could be due to surface tension variations produced by temperature, or concentration, gradients.

When a liquid/gas or liquid/liquid interface exists, Marangoni convection appears, provided some critical value of a parameter, called the Marangoni number, is exceeded. For a liquid layer of thickness d, the (thermal) Marangoni number is defined as:

$$\mathrm{Ma} = \frac{(-d\sigma/d\mathrm{T})\Delta\mathrm{T}d}{\mu a} \qquad (1)$$

where σ is the surface tension, $\Delta\mathrm{T}$ the temperature difference across the layer, μ the dynamic viscosity, and a the thermal diffusivity of the liquid.

For a few special cases, the critical values of the Marangoni number are known. The results of three different linear stability analyses are presented in Figure 1, where the wave number k of the disturbance (defined as 2π times the ratio of the fluid layer thickness to the wavelength of the particular disturbance) are plotted versus the corresponding neutral stability Marangoni numbers. The resulting curves give the frontier between stable and unstable perturbations. In all three models considered, an initially flat layer of liquid in contact with an infinitely deep air layer is heated from a bottom surface. Buoyancy effects are neglected in any case.

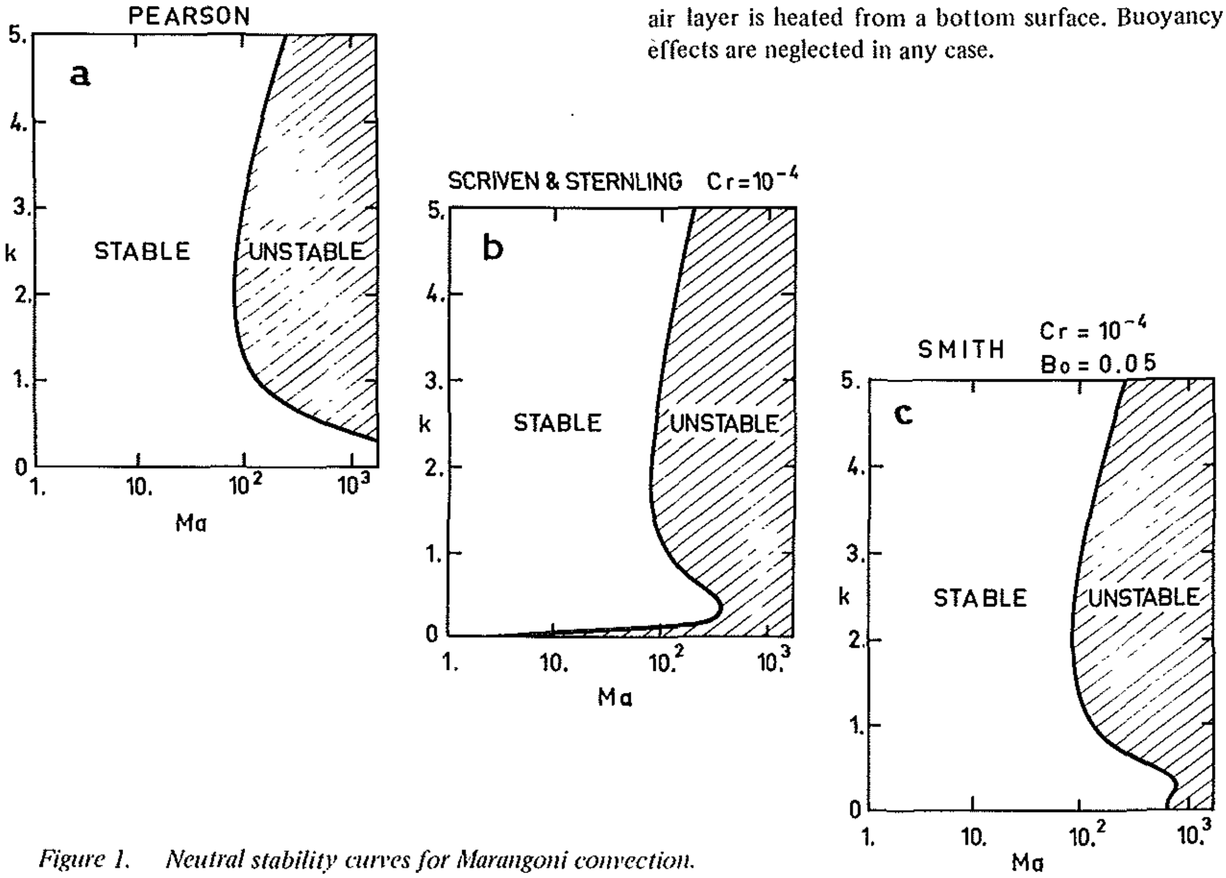


Figure 1. Neutral stability curves for Marangoni convection.

In Pearson's model[8] (Fig. 1a), the liquid air interface was not deformed in the normal direction, which amounts to assuming that σ is infinite. The results indicate the existence of a critical Marangoni number of about 80 for a wave number of about 2.0.

Scriven & Sternling[9] included the deflection of the free surface, considering surface capillary waves but not surface gravity waves. Figure 1b shows that disturbances with zero wave number are always unstable, and hence no critical Marangoni number exists. The dimensionless number Cr in the figure is the Crispation group, defined as:

$$\mathrm{Cr} = \frac{\mu a}{\sigma d} \tag{2}$$

which is the ratio of viscosity forces to surface traction forces. In Pearson's model, Cr=0.

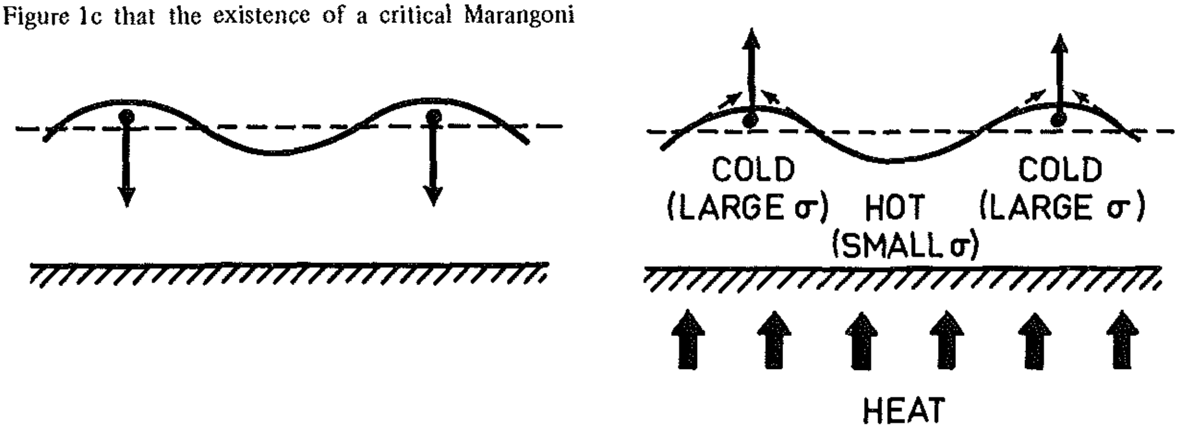
Smith[10] took into account the effect of surface gravity waves at the interface. It may be seen in Figure 1c that the existence of a critical Marangoni number is assured and that for small Cr this critical value is essentially that corresponding to a non-deformable interface. The Bond number which appears in Figure 1b expresses the ratio of gravity to surface tension-forces normal to the surface, and is given by

$$\mathrm{Bo} = \frac{\rho g d^2}{\sigma} \tag{3}$$

In the cases of Figures 1a and b, Bo is obviously zero.

Figure 2 is intended to illustrate how gravity tends to offset the effect of surface tractions, damping the perturbations corresponding to long waves.

Since surface gravity waves are not present under zero-gravity conditions, the main lesson to be learned from Figure 1 is that, although on Earth a minimum temperature gradient should be exceeded to induce instabilities, in space this threshold effect does not exist.



EFFECT OF GRAVITY ON LONG SURFACE WAVES

EFFECT OF SURFACE TENSION ON LONG SURFACE WAVES

Figure 2. In the case of long surface waves gravity damps Marangoni instability.

3. THE SPHERICAL DIFFUSION FLAME

A diffusion flame is a combustion process in which the reactants are not premixed. For most fuels at normal pressures, the chemical reaction rates are fast compared with the rates of mass and heat transfer, so that fuel and oxidiser react as soon as they reach the combustion zone, which is normally extremely thin (flame front). The chemical reaction rate is so high that both reacting species do not coexist on either side of the flame front, but they arrive in the appropriate (stoichiometric) relation to it.

Examples of diffusion flames are an ordinary candle and a fuel burning in an oxidising atmosphere.

The combustion of single droplets has been extensively investigated in relation to gas turbines, jet engines and rocket motors.

The first theory of the burning of a fuel droplet is that by Godsave[11], based partly on the following three simplifying assumptions, which are relevant to our discussion:

(a) The configuration has spherical symmetry.
(b) There is only radial convection transporting the fuel from the evaporating droplet surface to the reaction zone.
(c) Although the droplet radius decreases with time, quasi-steady-state conditions prevail.

Figure 3 outlines the distribution of species (fuel, oxidiser products) and temperature predicted by this simple model, which strictly speaking is only valid under zero-gravity conditions, since on Earth buoyancy-induced convection changes the aerodynamic field, distorting the shape of the flame. Figure 4 shows a more realistic flame shape under normal gravity conditions.

The main results obtained from the theory mentioned above are the following:

(a) The mass fuel consumption is a linear function of the droplet radius; it is very sensitive to flame temperature, but not to droplet temperature, which as a matter of fact is assumed to be constant and equal to the boiling temperature of the fuel.
(b) The flame to droplet radius ratio is constant for given values of the physico-chemical parameters.
(c) The droplet diameter D changes with time according to the relation

$$D^2 = D_0{}^2 - \mathrm{K}t \qquad (4)$$

where D_0 is the initial droplet diameter, t is the time, and K the so-called 'burning-rate constant', which is independent of time. This equation is similar to that expressing the relationship between diameter and time for vaporising droplets in the absence of combustion, which was observed experimentally, the values of evaporation and burning constants obviously being different.

Experiments on the burning of stationary droplets, suspended from quartz or metal filaments, under normal gravity conditions and with no forced convection, have been reported many times. The experimental technique involves recording the entire combustion of the droplet photographically, from ignition to final consumption. From these experiments it is deduced that:

(a) The flame shape of a stationary droplet is strongly influenced by free convection. The greater portion of the evaporated fuels burns at the upper part of the flame, where the process resembles that of a cylindrical diffusion flame.
(b) It is possible to calculate a flame to droplet radius ratio, defining a flame radius either by means of a, b, or h (Fig. 4). This ratio, being a function of droplet radius, is not constant, probably due to the influence of the cylindrical flame. The combustion of large stationary droplets is not very similar to the combustion of smaller ones, in which convection effects may be neglected.

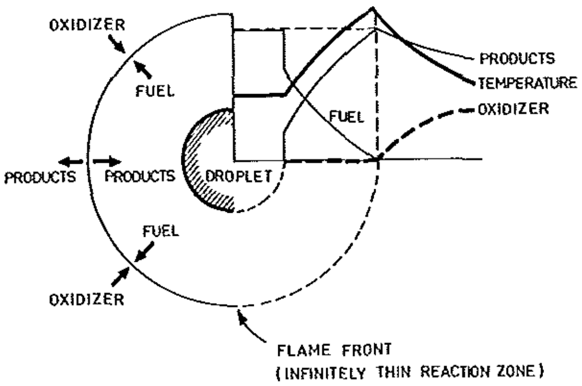


Figure 3. Theoretical model of a droplet combustion.

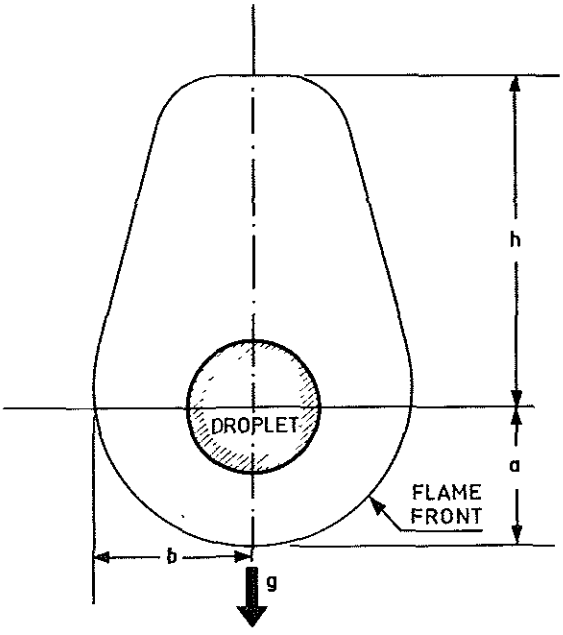


Figure 4. Flame shape under normal gravity conditions.

(c) Equation (4) is valid and the predicted values of the burning-rate constants are in fair agreement with those deduced following the life of the burning droplet. However, the knowledge of transport coefficients and chemical constants is so imprecise that neither agreement nor discrepancy can be considered to be significant.

Summarising: it is a fairly well established fact that Godsave's model gives a reasonable approximation of the experimentally measured burning rates, but a quite inaccurate picture of the flame shape.

A complete series of very well planned experiments on the combustion of droplets under zero-gravity conditions, using a free falling chamber, have been performed by Kumagai and collaborators and reported in three succesive papers[12-14].

The main contributions from these experiments are:

(a) The configuration has spherical symmetry, distorted only when a filament is used to support the droplet.

(b) Even under zero-gravity conditions, the flame to droplet radius ratio varies with time. As the fuel droplet is consumed, the flame radius increases and then decreases. The flame radius of fuel droplets of larger initial radius is always larger than that of fuel droplets of smaller initial radius. It appears that the flame radius depends primarily on the evaporated mass, and secondarily on the diffusion process.

(c) Equation (4) is still valid, but the values of the burning-rate constant for the zero-gravity combustion of filament-supported droplets are about 60% of those under normal gravity. Once the droplet is ignited, the temperature of the zone inside the flame front very soon reaches its steady-state distribution, because the heat capacity of the gas involved is very small. Under such conditions, the burning rate is barely influenced by the variation in the flame radius, and therefore the burning rate is almost constant.

(d) The supporting filament changes the value of the evaporation constant. Kumagai, Sakai & Okajima have recently found that the evaporation constant for a free droplet under zero-gravity conditions is larger than that for a suspended fuel droplet, but smaller than that corresponding to the suspended fuel droplet burning under the influence of natural convection. In any case, the filament distorts the droplet, so that the value of the evaporation constant depends somewhat on the length used to define the equivalent diameter of an otherwise nonspherical droplet. In addition, the thermal conductivity of the filament, which could be either high or low, changes the heat transfer from flame to droplet and consequently the evaporation rate.

This is a case where zero-gravity conditions have been reproduced in a comparatively inexpensive experiment to elucidate the validity of an extremely simple model of droplet combustion. We must now ask ourselves whether these experiments have any relevance to the study of spacecraft fire propagation.

In many cases, long experiments are required, and then the free falling tests may be appropriate. However, the knowledge gained from these simple experiments must not be underrated, though unexpected long-term effects may appear, such as those reported by Kimzey[15].

4. DYNAMICS OF LIQUIDS CONTAINING BUBBLES

Liquid-bubble dynamics is obviously a field of interest for space processing, particularly in connection with some manufacturing processes and with boiling heat transfer under reduced gravity conditions.

In most manufacturing processes, the degassing of the material when still in a liquid phase is a basic requirement for obtaining a useful engineering product. On Earth, the degassing is aided by buoyancy forces which cause the entrained gas bubbles to rise to the surface and escape. In an orbital workshop, however, buoyancy forces are not available and the elimination of gas bubbles from the molten material may be a serious problem. Rotation of the melt has been proposed by Bauer & Siekmann[16] as a method of inducing an artificial gravity, but to rotate a melt remotely is not always easy.

In recent years, considerable attention has been devoted to pool- and forced-convection boiling under reduced gravity conditions. Interest in these problems has been prompted mainly by the use of cryogenic fluids as propellants in today's spacecraft. Cryogens have a high specific impulse but have the disadvantage of a low equilibrium temperature, which can result in vapour generation even when subjected to low heat transfer rates, and a corresponding rise in the tank pressure. In some cases venting may be a solution to tank-pressure problems, but in long-term space flights and under low-gravity it could result in the loss of propellant.

Pool boiling occurs as local temperatures, in an otherwise stagnant liquid, exceed the saturation temperature. During the boiling process, there is liquid motion caused by free convection currents, as well as additional agitation because of the bubbles growing and collapsing. In order to produce the minimum noticeable boiling (discrete bubble regime), the heater surface must exceed the saturation temperature of the liquid by some perceptible amount. However, the liquid surrounding the heater may be below the saturation temperature, so that sufficient heat may be transferred from the vapour bubble to the coder liquid, and the bubble may condense and collapse (subcooling). For higher heating rates, a continuous blanket of vapour appears, surrounding the heater; this is known as burn out or film boiling regime.

The effect of subcooling and gravity level on pool boiling in the discrete bubble regime has been considered both theoretically and experimentally by Cochran & Aydelott[17]. When using a 100-ft drop tower (the NASA Lewis Research Center Drop Tower Facility) they noticed that:

(a) Boiling phenomena are gravity-independent in the discrete bubble regime for high subcooling. In particular, the dynamic contact angle between the bubble and the heating surface did not appear to be affected either by subcooling or gravity level.

(b) At low subcooling, dynamic forces associated with the nonsteady hydrodynamic field that surrounds the bubble play a more important role in removing bubbles with zero gravity than with normal gravity (at least if the heating surface is placed below the liquid layer).

(c) Under zero-gravity conditions, when the liquid temperature is close to the saturation point, the vapour generated is unable to emigrate from the vicinity of the heating surface, accelerating the presence of film boiling.

The behaviour of forced-convection boiling in zero-gravity has been considered by several authors. Ulianov & Aladiev[18] studied the high heat-flux regime near film boiling, while Cochran[19] considered the near-inception case. In both investigations drop-tower facilities were used. As may be expected, the gravity level does not substantially affect the evolution of the process, unless both subcooling and fluid velocity are kept sufficiently small.

Although it is undeniable that some relevant problems of sound spatial interest still remain to be solved in this field, there are some more mundane fields in which the presence or absence of gravity is of some interest; the method used on Earth to measure the speed of sound in a liquid containing bubbles is one such example. The acoustic properties of a bubbly mixture, such as found in the wake of a ship, may be used to detect the ship's presence. In addition, pressure disturbances travel at the speed of sound, so that this speed may be of interest for some cavitation problems that occur both on Earth and in space.

Figure 5 shows the apparatus used by Silberman [20] to measure the velocity of sound. A pipe was filled with water to various depths and bubbles were injected from submerged orifices. Diaphragm-type sound generators were placed flush with the bottom of the pipe, with the diaphragm normal to the pipe's axis. The upper surfaces were open to the atmosphere, so that sound waves were almost completely

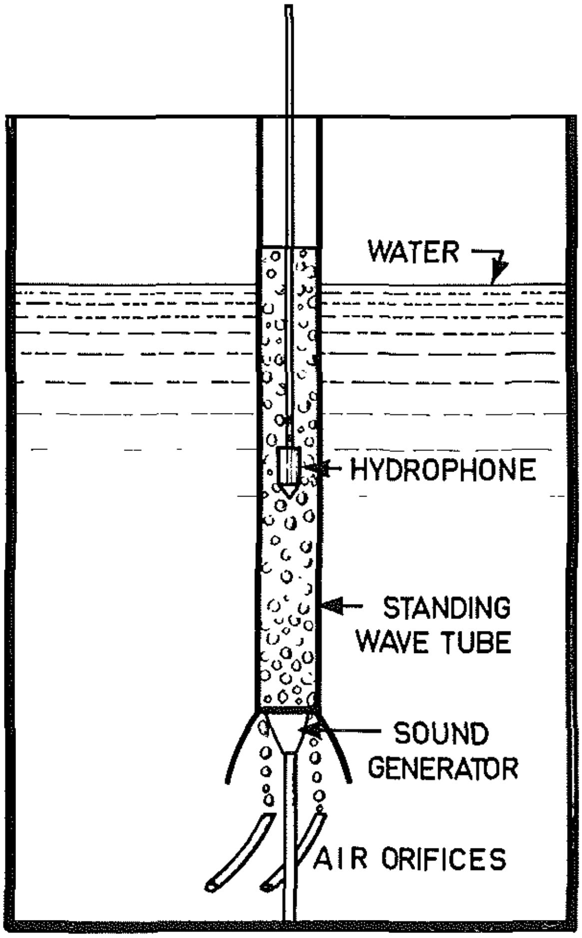


Figure 5. Sketch of apparatus used to measure the sound velocity.

reflected, while the air escaped freely. Sound-pressure measurements were made with small hydrophones moved along the pipe's axis.

Although it is clearly possible to measure the speed of sound using the above apparatus, the question now is what sound speed is being measured?

It has been common practice, at least in problems dealing with the flow of a gas containing heavy particles, to distinguish between equilibrium and frozen sound speeds. The equilibrium sound speed is obtained when particles and gas move together at the same velocity, while the frozen sound speed is obtained when the particles do not move.

Even neglecting the influence of buoyancy, the speed of sound depends on the disturbances that the sound wave induces in the two-phase flow. Crespo[21] has calculated the speed of propagation of a monochromatic sound wave through a liquid containing bubbles. He has assumed that the radius of the bubbles and the distances between them are small compared with the wavelength of sound and, in addition, that both phases are in mechanical equilibrium.

The resulting sound speed is a function of the ratios K and K' between bubble and liquid perturbation velocities and temperatures. These ratios in turn depend on the local interaction of each bubble with the surrounding liquid, and cannot be calculated easily, except in some particular cases.

The ratio K, which depends on the hydrodynamic interaction between the bubble and its surroundings, is a function of the Reynolds number (Re) defined in terms of a characteristic velocity, the bubble radius a, and the kinematic viscosity of the liquid υ_0. When the fluid is only disturbed by the sound, a typical characteristic velocity may be ωa, where ω is the angular frequency of the sound wave. If this Reynolds number is small enough, we expect that viscous forces, which are then dominant, will drag the suspension along with the fluid, so that K = 1; if inertia forces are dominant, the hydrodynamic field surrounding the bubble will be much more complicated and fairly sensitive to Reynolds number changes, provided that this number does not exceed some critical value.

For the ratio K' of bubble to surrounding liquid perturbation temperatures, Crespo has shown that heat transfer is a function of the product of the Reynolds number (Re), defined as above, multiplied by the Prandtl number (Pr), which measures the ratio of viscous to thermal diffusivities in the bubble, and by the ratio of liquid to bubble kinematic viscosities. When this number is small enough, the thermal diffusivities dominate and both species will be at the same temperature, but when it is large the fluid behaves isentropically.

From these considerations it is deduced that the speed of sound depends on the fine details of the interaction between the bubble and the surrounding liquid. When buoyancy carries away the bubbles as in Figure 5, it will have an effect on the measured velocity. As far as is known to the author, no experiment has been performed to clarify how remarkable this effect is, so that it should be of interest to examine the data presented in Table 2, which illustrates how the frequency of the sound waves influences the sound speed in an air-water mixture. In Table 2, X is the volume fraction occupied by the bubbles and, in order to compare results, the ratio of the pertinent sound speed c to equilibrium sound speed c_e (K = K' = 1) is presented.

Table 2. Influence of frequency on sound speed.

Case	c^2/c_e^2	Observations
$Re_0 << 1 << \nu_1/\nu_0 Pr_1$	1	Equilibrium case
$1 << Re_0 << \nu_1/\nu_0 Pr_1$	$1+2X(1-X)\Gamma^{-1}$	Γ depends on X and the bubble shape. When $X << 1$ and the bubbles are spherical, $\Gamma = 1$.
$1 << \nu_1/\nu_0 Pr_1 << Re_0$	$(1+2X(1-X)\Gamma^{-1})\gamma$	γ is the ratio of specific heats for air ($\gamma = 1.4$)

Subscripts $_0$ and $_1$ indicate water and air, respectively.

For $X = 0.2$, c^2/c_e^2 would be of the order of 1.3 in the second case, and of the order of 1.8 in the last one. This gives an indication of the importance of local effects. In addition, it should be pointed out that it is by no means clear whether intermediate cases give intermediate values of c/c_e or not, and that the influence of buoyancy cannot be taken into account easily. For these reasons, it is suggested that the sound speed through a liquid containing bubbles should be measured under reduced gravity conditions.

5. CONCLUSIONS

The Spacelab provides many opportunities for conducting experiments either of basic scientific interest, or oriented to future applications (or both). The provision of long-term zero-gravity conditions is the most conspicuous benefit and the one whose reproduction on Earth involves the greatest difficulties.

One of the main attractions of the space workshop is the supposed absence of fluid convection under reduced gravity conditions. It should, however, be pointed out that, although gravity-induced convection is absent, many instability mechanisms still remain, rendering illusory several advantages of space processing that are based on the extended, but incorrect, assumption that no convection exists under zero-gravity conditions.

The possibility of either avoiding or inducing convection, and the development of procedures to detect low-velocity fluid motions, will pose some interesting fluid-dynamics problems in the near future.

When long-term effects are not important, the required low-gravity conditions may be attained fairly inexpensively using drop towers, aircraft prepared for weightless flight, rockets and the like, but substantial work should be done to develop methods to avoid the vibratory effects that are sometimes present when these facilities are used.

Finally, the importance of an appropriate selection of really interesting problems in planning future Spacelab activities should be emphasised together with the fact that, with the present state of the art, very worthwhile knowledge should be gained from extremely simple experiments.

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