JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 11, No. 1, January–March 1997

Aerodynamic Trapping and Laser Heating for Containerless Glass Processing in Microgravity

François Babin,* Paul-François Paradis,† and Jean-Marie Gagné‡
École Polytechnique de Montréal, Montreal, Quebec H3C 3A7, Canada

In analyzing the characteristics of the aerodynamic trap-laser heating apparatus, it is shown that it possesses most of the qualities needed for containerless glass (or other material) processing, on the ground and in reduced gravity. Some of the effects of laser heating and melting, and of aerodynamic trapping are studied with respect to their influence on vitrification and glass quality, especially in reduced gravity. The experiments were carried out on very high melting point (over 1500 K) silica and alumina bearing compounds, and in particular calcium aluminate. With the flight hardware, it was possible to vitrify, on the ground, 3.6-mm-diam spherical samples of 50CaO–50Al_2O_3 (CA) (%mol), with a 100-W, 3-mm spot, CO_2 laser beam, and a 0.5-l/min gas flow. Alumina samples were successfully melted during aircraft parabolic flights. A discussion of trapping ability with respect to sample temperature (and viscosity) is presented.

Introduction

CONTAINERLESS processing can eliminate heterogeneous nucleation, thus reducing the critical cooling rate and extending the vitrification range to new compositions or larger samples. A containerless process also eliminates impurities originating from the container, allows the processing of chemically reactive materials and helps in studying vitrification or homogeneous nucleation. The technological goal of containerless glass processing is producing new or better quality glasses with tailored or improved optical, mechanical, and chemical properties.

It has been proposed[1–3] that microgravity processing might further enhance the vitrification range and/or help in studying vitrification, homogeneous nucleation, or diffusion-controlled processes. This would again help in producing new and improved glasses. Microgravity eliminates or reduces many undesirable effects: buoyancy, sedimentation, gravity-driven convection, hydrostatic pressure, sagging, gravity-driven surface waves, etc. The disappearance of these effects renders others more easily observable.

The ultimate goal of our project is to study, by using a containerless technique, the influence of gravity, or lack of, on the vitrification of silicate and aluminate compounds, and in particular calcium aluminate. These last compounds are interesting as windows in the infrared or as laser material.[4,5] They have high melting points (>1800 K), and vitrification is difficult or impossible on the ground, even with containerless techniques.

On the ground, containerless processing requires a positioning system that levitates a sample and holds it at a specific point in space. Reduced gravity should simplify containerless processing, forces needed to position or hold, without contact, a sample at a specific point in space being much smaller than on the ground (but not zero, since there is a residual and continuously varying acceleration vector in reduced gravity).

The most promising reduced gravity containerless dielectric glass processing techniques are the gas film levitator (GFL),[6] the aerodynamic trap (ADT),[7,8] and different acoustic systems (AAL, DRUMS)[9,10] (these techniques allow control over the processing gas). We chose to study the aerodynamic trap as a positioner because of its simplicity and low cost.

Containerless glass processing also requires an energy source for heating and melting the samples. We chose for this purpose CO_2 laser beam heating. The laser beam allows us, among other things, to rapidly raise the sample temperature to over 2500 K.

We will compare the qualities and faults of the ADT–laser system with the abilities required from a reduced gravity containerless processing facility as described by Zarzycki et al.[3] In addition, some effects induced by the gas flow of the ADT and by laser beam heating are observed and investigated. What is the influence of these effects on vitrification and glass quality (optical properties, structure, morphology, etc.), especially in reduced gravity? Very little research has been done on the thermal, mechanical, and optical effects of laser light in reduced gravity.[11–14]

This article starts with a brief description of the aerodynamic trap and of the ADT–laser system for contactless processing. Its potential for reduced gravity glass (or other material) processing is discussed. The setups are then described along with experiments done on the ground and in reduced gravity. Some results are presented with a discussion on effects associated with laser heating and melting, aerodynamic trapping, and vitrification in these conditions.

Hardware

Aerodynamic Trap

The ADT is interesting for two main reasons. First, it has proven to be a good method for producing glass on Earth,[15,16] and second, its trapping ability has been recognized.[17,18] Positioning and trapping were achieved, with the ADT, on the ground and in reduced gravity, in isothermal room temperature conditions as well as at very high temperatures (>2000 K),[7] for solids and liquids.

The ADT trap consists of an aerodynamic diffuser (axisymmetric duct), which allows a fully developed flow to expand, creating a vortex ring. A sample sphere is placed in the duct. It is trapped downstream from the vortex plane,[19,20] on the axis of the duct (when flow and residual forces are collinear).[7] Different duct geometries and materials are possible and have

Presented as Paper 96-0924 at the AIAA 34th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 15–19, 1996; received April 1, 1996; revision received Aug. 5, 1996; accepted for publication Aug. 6, 1996.

*Research Physicist, Département de Génie Physique.
†Graduate Student, Département de Génie Physique. AIAA Member.
‡Professor of Engineering Physics, Laboratoire d'Optique et de Spectroscopie.

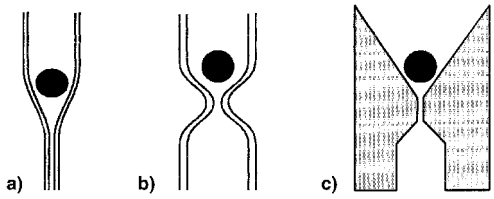

Fig. 1 Diffusers: a) quartz capillary–divergent, b) quartz convergent–divergent, and c) aluminium convergent–divergent.

been successfully tried (Fig. 1). Recently, cylinders have been trapped in an appropriately designed ADT.

Features required from a microgravity containerless glass-processing facility were detailed by Zarzycki et al.[3] The ADT–laser system possesses most of these required features. The ADT itself is well adapted to a reduced gravity environment characterized by variations in acceleration (in amplitude and direction, such as with the KC-135). It can contactlessly trap a sample in space and time without active feedback. Spheres (and, eventually, cylinders) of various sizes can be trapped (from a millimeter-sized sphere to a ping-pong ball). These samples can change in size while being processed (for example, by evaporation). Trapping is independent of the electrical properties of the sample (dielectrics, metals, or superconductors). The ADT works in a wide range of temperatures with almost any processing gas. Use of ultrahigh purity gases significantly reduces contamination. Solids as well as low-viscosity liquids (like high-temperature liquid alumina having a viscosity of approximately 0.03 Pa s) can be containerlessly processed.[7,8]

Since trapping is done in an expanding duct, the opening allows easy access and viewing for diagnostics such as pyrometry, thermography, or spectroscopy. Sample behavior while heating, melting, and resolidifying can be followed with a video camera. The ADT geometry is also well suited for laser heating and processing.

Laser

For heating the samples, we chose a 120-W, continuous-wave CO_2 laser, the 10.6-μm radiation being absorbed by most dielectric materials and the laser beam being easy to manipulate and focus. Practically 100% of the radiation is absorbed at higher temperatures. With this radiation source we can heat (from room temperature to more than 2500 K) and melt a 3-mm-trapped sample within a few seconds, rapid solidification then being possible in the reduced gravity portion of a KC-135 parabola (or other parabolic aircraft). Only the sample is directly heated with this noncontact radiative heat source. These features allow a more direct and instantaneous control over the heat input to the sample.

ADT–Laser Processing Facility

The preceding discussion on how the ADT or laser features fit into microgravity containerless glass processing is now extended to the system as a whole, beginning with the cooling rate. The cooling rate can be controlled in many ways when we start with a very high-temperature sample. At these very high temperatures, energy is lost mainly by blackbody radiation. For faster cooling, the size of the sample is reduced and laser power is turned off instantly. For slower cooling, the size of the sample is enlarged or the laser power turned off gradually. The nature of the trapping gas and flow rate can also be modified to affect the cooling rate, especially at lower temperatures.

This system has the added advantage that only the sample is very hot, rendering the observation with a camera easier, the sample glowing much more than the background. This also simplifies pyrometry. Moreover, the use of this system may not be restricted to glass processing. It could be used, for example, for thermophysical properties measurements.[21]

Issues such as homogenization in temperature and composition or fining are difficult to tackle beforehand and are measured during the experiments on the ground and in microgravity to evaluate different effects.

For the experiments on the ground and in reduced gravity, the laser and the ADT are installed in the laser test-bed system (LTS), a multiuser test facility owned by the Canadian Space Agency.[22] This facility was built to fly on the NASA KC-135 aircraft.

An important part of the actual facility is the trap. A trap consists of a diffuser as shown in Fig. 1. Many of these traps were built and tested on the ground and in reduced gravity.[7,8] For the last parabolic flights, a carousel of 40 traps was installed in the LTS, to fully use reduced gravity time (these flights were done in February of 1994 and 1995). In 1994 the traps were converging–diverging quartz diffusers (Fig. 1b), whereas in 1995 they were aluminium diffusers (Fig. 1c). They have different divergent angles, although some angles are preferable.[8] They all have an approximately 1-mm throat diameter. The other important component is the laser. The Melles Griot CO_2 laser beam is always directed upstream (in the direction opposite that of the gas flow), using appropriate optical components (shutter, mirrors, ZnSe lenses, and windows).

The ground (Fig. 2a) and microgravity facilities (Fig. 2b) also include a monochromatic silicon detector, used to measure the light output from the sample, at 700 nm (using an interference filter). This monochromatic detector is used as a fast pyrometer to measure apparent temperature (because crystallization and vitrification occur in the first seconds after the laser beam shutter is closed). The detector can measure light from a point on the sample or from all of the sample. The pyrometer is calibrated using the rapid recalescence of alumina to 2327 K. A high-resolution video camera is used to follow processing, observe heating, melting and resolidification, and associated laser, ADT, or reduced gravity effects. The camera can look through the diffuser when it is in quartz, or from the

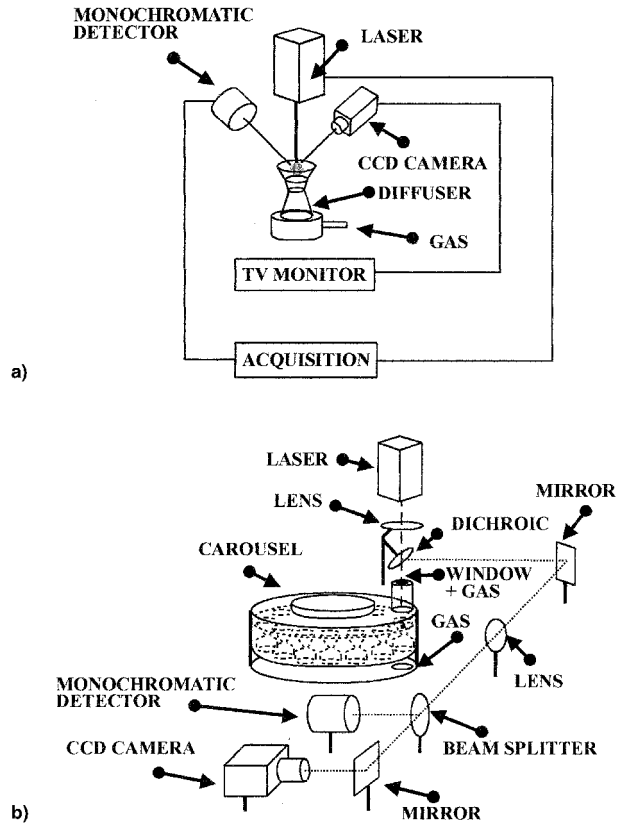

Fig. 2 Experimental facilities: a) ground and b) microgravity (February 1995).

top when it is in aluminium or quartz. Images are stored on tape with a video recorder. Data acquisition equipment is available for recording temperature, laser power, and gravity levels.

Experiments

Sample Preparation

The samples are mostly alumina- and silica-based compounds (although other types were processed for different reasons, those cited here are examples), having a spherical shape with an approximate 3 mm diam. They come from a variety of sources; the High Temperature Physics Laboratory (CRPHT) of the French CNRS, Industrial Tectonics Inc., and ourselves. The powders used by ourselves and the CRPHT come from the CRPHT.[23] They are synthesized by atomization or sol–gel techniques that produce very fine and homogeneous starting powders. Heating the powder to approximately 900 K eliminates the organic residues introduced during synthesis. The residues (impurities) can cause bubbles and heterogeneous nucleation. Getting rid of these residues also minimizes shrinkage when processing containerlessly. Powders are then compacted with an isostatic press at 2000 bar. A piece of compacted powder is then introduced in the diffuser, laser heated, melted, and fined (fining being most important at the beginning of the process). When melted, the sample takes a spherical shape if it is small enough not to sag. The spherical shape comes from the equilibrium between surface tension and vapor pressure.[24] Cooling occurs when the laser power is turned down, instantaneously or gradually. These samples are then processed again on the ground or in reduced gravity, analyzed, and compared.

Sample Processing

To process the sample and study trapping, heating, melting, and vitrification, we introduce a spherical sample into a diffuser. The gas flow for trapping is usually set between 0–5 l/min. The laser power is then raised gradually. The sample heats up and melts. When the sample is heated and melted on the ground, it is naturally stable because of buoyancy, if the colder solid is denser than the hot liquid (the top is heated and liquified). Gravity-driven convection is impossible in the heated liquid since the top is hotter than the bottom, but it is possible in the surrounding gas.

Processing is observed with the video camera. This allows us to study the features and behavior of the sample; external motions (rotation, oscillations); internal motions (convections, bubble migration, and sample deformation, etc.); and light emission (giving an idea of thermal gradients, solidification and melting fronts, recalescence, bubble motion, and convections, etc.). Temperature profile while processing is stored and studied afterward for measurements of cooling rates, undercooling, and maximum processing temperature, etc.

Observations

Trapping Stability

Trapping and positioning of ambient and high-temperature spheres was discussed in a previous paper.[8] Let us recall that the sample usually rotates around the symmetry axis of the diffuser. The speed of rotation depends on flow rate, temperature, surface roughness, and sphericity of the sample. The higher the flow rate, the faster the rotation. But as temperature rises, rotation speed falls. Rotation seems to stop when the sample is molten. When the sample cools and solidifies, it might take an aspherical shape, especially if it crystallizes; it then rotates again.

In addition to rotation, the sample moves around in the diffuser, away from the stable equilibrium position. The effect of the gas flow on the sample stability inside the diffuser depends to a large extent on its sphericity, especially in reduced gravity. Smaller flow rates do not perturb the sample as much as larger flow rates.

The stability of the samples also depends on residual accelerations. The KC-135 environment is subject to more acceleration variations in all directions than the ground environment. This causes aerodynamic forces to vary over the sample surface (solid or liquid) and reduces stability, especially in the reduced gravity portion of the parabola, gravity not pulling the sample back toward the equilibrium point. In this case, larger flow rates are preferable to trap more strongly and damp the oscillations.

If the lack of stability of the sample is such that it leaves the trapping zone, it can be blown away or fall back in the diffuser, depending on gravity level and flow rate.

In going from a high level of gravity to a reduced gravity environment, the sample rises in the diffuser, the stable equilibrium point being 100–200 μm higher. This was predicted by theory.[7,8]

Varying thermal gradients and temperatures induced while laser heating or cooling the sample also affect the stability. Changing density, viscosity, and flow patterns in the trapping gas affect the aerodynamic forces exerted on the sample. The trapping effect is smaller at very high temperatures (measured on the top of the sample to be >1500 K). The combined effect of high flow rate and high temperature usually expels the sample from the trap.

Melting part or all of the sample is another parameter for stability, depending on viscosity, surface tension, and size of the sample on one part and flow rate and viscosity of the gas on the other part. When the sample is unstable and partly molten, it can stick to the diffuser, generating heterogeneous nucleation and crystallization while cooling.

Laser Heating and Melting

The laser generates a TEM_{00} beam of 10.6-μm coherent light. The transverse power distribution of this beam of radiant energy is Gaussian. It can be focused to a spot size of 40 μm, generating power densities close to 10^7 W/cm^2. The energy input to the sample can vary between 0 and 100–120 J/s on an area of 40 μm diam or on the totality of the upper half of the sample.

When the sample is placed at the focus of the high-power beam (100 W), the heat input is sufficient to drill a hole in the sample, evaporating the material in its path and creating a plume (Fig. 3a). In most circumstances, the focused laser levels off (or shatters) the top of the moving (oscillating or rotating) sample (Fig. 3b). The very high local temperature va-

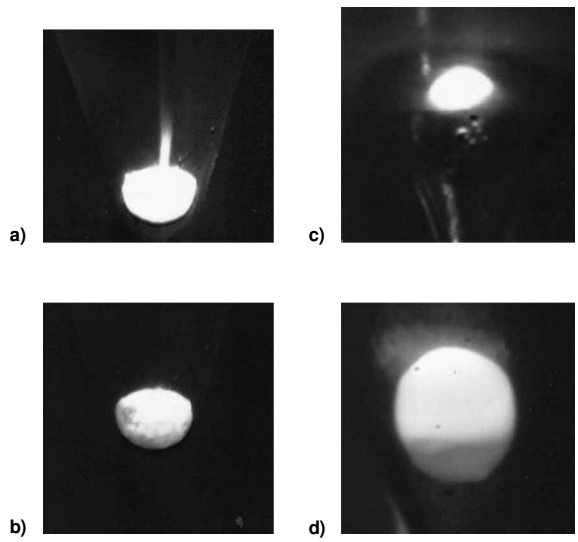

Fig. 3 Effects associated with laser heating: a) evaporation plume (alumina), b) leveled-off sample (alumina), c) thermal gradient (black glass), and d) melt zone (alumina).

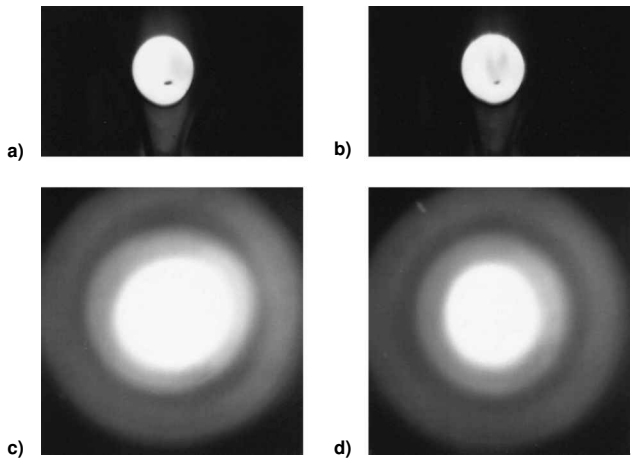

Fig. 4 Samples being processed in quartz (a and b) and metallic (c and d) diffusers: a) alumina in 2 g, b) alumina in μg, c) $CaAl_2O_4$ in 2 g and d) $CaAl_2O_4$ in μg.

porizes the top of the sample without melting it completely. These are not the proper processing parameters.

For correct processing, the sample is placed out of the focus of the laser beam. The spot size is between 1–3 mm. Laser power is raised at a proper rate, taking care not to induce thermal stress and shatter the sample. Laser light is absorbed almost totally on the surface of the sample. At the start of heating, the top part is hotter as seen from the glow (Fig. 3c). As time passes and as laser power is raised, the glow expands, the sample becoming hotter throughout. There is a thermal gradient because heat comes in from the top and because the sample is cooled on the bottom by the cold trapping gas. The molten zone can be distinguished from the nonspherical solid sample by its sphericity and smoothness (Fig. 3d). If, for some reason, the sample rotates and the axis of rotation varies, heating is much more uniform.

Heating and melting do not depend solely on laser energy input. Flow rate is another important parameter. When the flow rate is too high, the sample does not completely melt because too much heat is being forced away by the flowing gas. There is a stronger difference in temperature between the top and bottom of the sample. Moreover, the melted sample distorts at high flow rates, shatters, and/or leaves the trap. The heat loss depends on the flow rate and the nature of the gas.

With proper laser energy input and gas flow rate, we can heat and melt a sample on the ground or in reduced gravity. Figures 4a and 4b show a heated silica-based sample, in a quartz diffuser (seen from the side, laser beam coming in from the top, gas flow from the bottom), on the ground and in reduced gravity. Figures 4c and 4d show a heated 50% CaO–50% Al_2O_3 (CA) sample, in a metal diffuser (seen from the top, laser-heated part), on the ground, and in reduced gravity. When the sample is liquid, the surface is smooth and practically spherical, unless some perturbation induces distortions and oscillations. Small amplitude waves on the surface, caused by small perturbations, usually indicate that the sample is liquid.

Fining

On the ground, during the initial moments of laser heating and melting, bubbles migrate to the top of the sample, coalescing or bursting the surface. The number of bubbles diminishes rapidly if the melted sample has a low viscosity and a large temperature gradient. Sometimes a large bubble (more than 250 μm diam) stays on the top of the sample. Repeated heating–cooling cycles also help in fining, as does heating at higher temperatures or for longer periods. We have observed that bubbles coalesce at the center of the sample (when it rotates), and that in some cases, bubbles descend (observed in black glass).

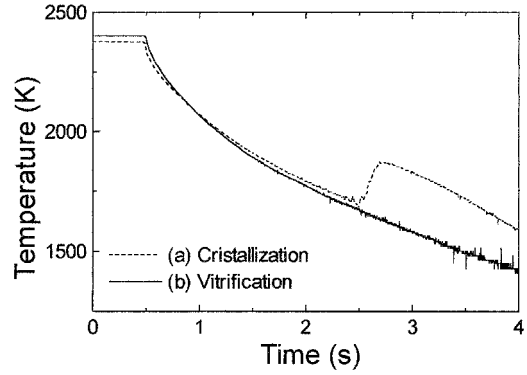

Fig. 5 Cooling curves on the ground.

Cooling and Vitrification

To produce a glass, we must cool the melted sample at an appropriate rate. Most of the compounds used in this study vitrify only at very high cooling rates. For fastest cooling we block the laser beam instantly with a shutter and use small diameter samples. Furthermore, very rapid cooling and vitrification are possible because the samples are at very high temperatures and energy is lost mainly by radiation. At these high temperatures, radiative heat loss is very efficient.

Apparent temperature is calculated supposing unit emissivity at the detector wavelength (700 nm) at all temperatures, which seems to be an adequate assumption at higher temperatures for alumina[25] and most other high-temperature samples. Cooling curves for CA, on the ground, are shown in Fig. 5. The samples are melted and heated to 2400 K (as in Refs. 26 and 27). Initial cooling is as high as 2000 K/s. The temperature drop is close to 700 K in the first 2 s. After this initial cooling, the sample may polycrystallize rapidly as in Fig. 5a, causing a large bump in the cooling curve. Undercooling is close to 200 K in this case. Larger undercoolings are possible. The sample can also mainly vitrify, as in Fig. 5b, and have a smooth cooling curve.

Cooling and vitrification depend on trapping gas flow rate. For 3-mm calcium aluminate samples heated with 100 W of laser power (with an appropriate energy density) in a 30-deg aluminium diffuser with a 1-mm throat diameter, it is impossible to vitrify a sample at flow rates of more than 1.3 l/min. Cooling and vitrification also depend on sample size. With the same settings as used previously, but with a low flow rate of 0.5 l/min, vitrification is possible only for samples of less than approximately 3.6 mm. Within these limits, glasses can be made with 50% CaO–50% Al_2O_3 samples (Nd doped or not), on the ground. Unfortunately, problems with the laser cooling unit kept us from going to more than around 1700 K during the flight experiments.

Discussion

It is clear that for proper processing, the sample in the trap must be stable. This means using as low a flow rate as possible (but the sample must be trapped and oscillations damped sufficiently) and an unfocused laser beam (between 2–3 mm in diameter). Samples must be close to spherical to minimize rotation.

After stability, heating is the next concern. How the heat is distributed in the sample depends on many parameters. It depends on heat input and output and on heat transfer inside the sample. The input is the laser light. Laser light does not penetrate far into the sample. The 10.6-μm radiation is completely absorbed close to the surface. This absorption generates heat. Since the energy distribution is Gaussian, so is the heat input. There should be a temperature gradient on the surface of the

sphere, the top being the hottest part. Heat is then distributed in the sample by conduction and radiant heat from the hotter parts (the relative importance of each depends on the transparency of the sample).

When the sample is colder and semitransparent, radiant heat is distributed according to the laws of light propagation inside a sphere of index of refraction n sitting in air ($n = 1$). This may generate hot spots inside the sphere. When bubbles are present, they act as microlenses, disturbing the radiant heat distribution inside the sample. Some bubbles seem brighter, others darker. Estimating temperatures from the distribution of light inside the sample (measured with a camera) is difficult because of these optical effects. When the sample becomes very hot, it usually becomes more opaque and heat is transferred mainly by conduction.

When the sample starts to melt or soften sufficiently, convection helps in distributing the heat. Convection plays a role in heat exchange inside the sample and from the sample to the exterior. Convection in the sample can be caused by thermocapillary forces or by the flowing gas on the surface of the sample. When the sample is melted, temperature gradients are less severe, indicating the importance of convection for temperature homogeneity.

On the other hand, heat is lost by radiation, conduction to the trapping gas, and evaporation. Radiative heat loss is much more important at very high temperatures, where the samples can be considered as blackbodies. At these high temperatures, heat is lost mainly by radiation. If radiant heat can be reflected back to the sample, the laser input power needed to process at high temperatures is diminished.[22] This is an advantage of metallic diffusers over quartz diffusers. If very rapid cooling is more important, quartz is then preferable.

Radiative heat loss is also more important for larger blackbody samples, since it depends on surface area. Less laser power is necessary to melt smaller samples.

The cold air flowing around the sample generates heat loss. Conduction between the hot sample and the cold air is the other main loss mechanism. Since air is flowing, it can be considered to always be at the same temperature on the bottom of the sample (it becomes warmer as it flows along the sample surface). Heat loss depends on the temperature difference between the cold gas and the hot sample and on the nature of the gas. Heat is forced away by the gas, and heat loss depends on flow rate.

When the sample is melted and is at a temperature of more than 2000 K, the shutter is closed, bringing the laser input to zero. Cooling then starts. In the first seconds, radiative heat loss is the main cooling mechanism. Afterwards, conduction and forced convection in the trapping gas are the main cooling mechanisms. Evaporation is neglected. Figure 6 shows the importance of each loss mechanism with respect to temperature for a 3-mm-diam sphere in 300 K air flowing at 1.5 l/min. Emissivity is taken to be equal to 1 and the radiative heat-loss curve represents an upper limit. For the heat lost in the flowing gas [$hA(T_{\text{sample}} - T_{\text{ambient}})$, h being the heat transfer coefficient, A the surface area of the sample, and T the temperature], Williams' formula[28] is used for h, whereas a hotter intermediate gas film close to the sphere [$T_{\text{film}} = (T_{\text{sample}} + T_{\text{ambient}})/2$] determines the Reynolds number and the thermal conductivity used in Williams formula. This gives an approximate value to the combined conduction–convection heat loss, although it seems overestimated if we compare with the total heat loss of 90 W given by Weber and Nordine[29] in similar conditions.

The temperature distribution inside the sample depends on many parameters; sample total emission and absorption, spectral emission and absorption, conduction inside the sample, conduction to the gas, convection in the sample, in the gas, flow rate, diffuser geometry, and material (reflection, absorption, emission, and conduction, etc.), and evaporation (if any). A simple model of the processing is difficult to achieve in these conditions, especially when we study heating and cooling, although some work as been done.[30] The thermal gradient between the top and bottom surfaces of the sample depends on sample diameter and is approximately 150 K (at the melting point) for a 3-mm-diam silica sample. The thermal gradient induces gradients of properties such as surface tension, concentrations, and density. For example, the surface tension of silica has a 3.1×10^{-5} N/m K temperature coefficient.[31]

There are other temperature effects. For example, if selective evaporation takes place, heating can be a means for controlling sample composition, along with oxygen content of the trapping gas.[32]

Forces responsible for convection in the liquid sample (thermocapillary forces and forces caused by the flowing gas on the surface of the sample) not only help in mixing, fining, and homogenizing the melt, but also distort it, affecting trap stability. The higher the flow rate, the stronger the distorting forces. The lower the sample viscosity (the higher the sample temperature), the stronger the distortion. The higher the flowing gas viscosity (or temperature), the stronger the distortion. For example,[33] CA at 2000 K has a viscosity of 0.13 Pa s. When heated to 2500 K, viscosity drops to 0.018 Pa s. In these same conditions an air film at a temperature of T, where T = (ambient temperature + sample temperature)/2, has a viscosity that goes from 473×10^{-7} to 530×10^{-7} Pa s.[34] The ratio of sample to gas viscosities thus goes from 2750 to 340. For these reasons, trapping gas flow must be as low as possible for high-

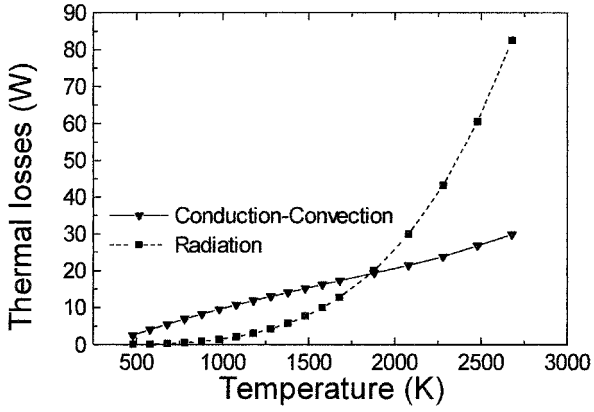

Fig. 6 Thermal losses for a 3-mm-diam sphere in 300 K air flowing at 1.5 l/min.

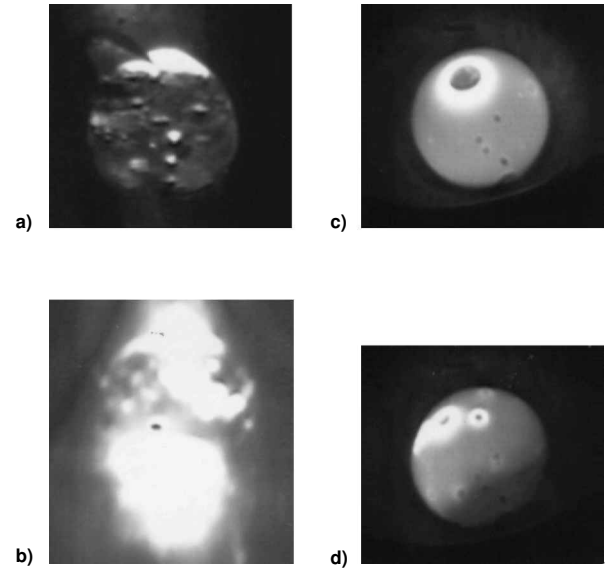

Fig. 7 Bubbles in different samples: a) BK-7, b) black glass, and both c) and d) CA.

temperature processing, and the sample must be kept viscous enough not to distort, be unstable, and leave the ADT.

As for fining, it seems clear that liquid movement in the sample (caused by thermocapillary forces or gas flow on the sample surface) helps in bringing the bubbles to the surface (especially useful in reduced gravity). Rotation of the sample helps in having the bubbles coalesce on an axis in the center of the sample. Bubble motion depends on convections, rotation of the sample, buoyancy, and thermal gradients, etc.

Fining is important for a good-quality optical glass, but is also important for accurate measurements of temperature and thermophysical properties. As shown in Fig. 7, bubbles can be bright, dark, generate bright spots, or have bright boundaries. These bubbles can affect the temperature measurements, when the pyrometer is focused onto one of them. On the ground, bubbles are frequently on top of the sample, where the pyrometric measurement is done. Having light from most of the sample fall on the detector and using multiple color pyrometry would be more advantageous than focusing on one small spot, even when there are gradients.

Once the bubbles are removed, the sample in the trap can cool and vitrify. Vitrification is more probable when the melt is homogeneous, in temperature and composition. This means low-melt viscosity (high-melt temperature) and small flow rates in small-angle diffusers. In these conditions, we were able to vitrify many different compositions and sizes.

Conclusions

The ADT–laser system is adequate for containerless materials processing in reduced gravity. With the LTS, it has most of the features required from a reduced gravity containerless glass processing facility. Even though we were able to containerlessly melt and solidify alumina in reduced gravity, working at very high temperatures is not straightforward. Much work has to be done on sample stability at very high temperatures in reduced gravity. For lower sample temperatures (less than 2000 K) and higher sample viscosities, trapping and processing is much simpler. Aerodynamic trapping is certainly a good candidate for lower temperature reduced gravity containerless glass processing (in air or other gases).

If the flow rate, gas viscosity, sample viscosity, and thermal gradients are such that there are no convections, diffusion-controlled phenomena can be studied.

Acknowledgments

This work was possible thanks to grants from the National Research Council of Canada and from the Canadian Space Agency. We wish to thank Y. Lemire and P. A. Dion for expert technical assistance. Special thanks also go to J. P. Coutures and all those who helped at the CRPHT. The authors also wish to thank S. Lévesque for help, discussions, and comments during this project.

References

[1]Kreidl, N. J., and Rindone, G. E., "Glass in Space," *Journal of Non-Crystalline Solids*, Vols. 38 and 39, Pt. II, 1980, pp. 825–830.

[2]Ray, C. S., and Day, D. E., "Glass Formation in Microgravity," *Materials Research Society Symposia Proceedings*, Vol. 87, 1987, pp. 239–251.

[3]Zarzycki, J., Frischat, G. H., and Herlach, D. M., "Glasses," *Fluid Sciences and Materials Science in Space*, Springer–Verlag, New York, 1987, pp. 599–636.

[4]Lines, M. E., MacChesney, J. B., Lyon, K. B., Bruce, A. J., Miller, A. E., and Nassau, K., "Calcium Aluminate Glasses as Potential Ultralow-Loss Optical Materials at 1.5–1.9 μm," *Journal of Non-Crystalline Solids*, Vol. 107, Nos. 2, 3, 1989, pp. 251–260.

[5]Tanabe, S., Ohayagi, T., and Soga, N., "Upconversion and Local Structure of Er^{3+} Doped Aluminate Glasses," *Journal of the Ceramic Society of Japan*, Vol. 101, No. 1, 1993, pp. 74–79.

[6]Potard, C., and Dusserre, P., "Contactless Positioning, Manipulation and Shaping of Liquids by Gas Bearing for Microgravity Applications," *Advances in Space Research*, Vol. 4, No. 5, 1984, pp. 105–108.

[7]Babin, F., Gagné, J.-M., Paradis, P.-F., Coutures, J.-P., and Rifflet, J.-C., "High Temperature Containerless Laser Processing of Dielectric Samples in Microgravity: Study of Aerodynamic Trapping," *Microgravity Science and Technology*, Vol. 7, No. 4, 1995, pp. 283–289.

[8]Paradis, P.-F., Babin, F., and Gagné, J.-M., "Study of the Aerodynamic Trap for Containerless Laser Materials Processing in Microgravity," *Review of Scientific Instruments*, Vol. 67, No. 1, 1996, pp. 262–270.

[9]Weber, J. K. R., Hampton, D. S., Rey, C. A., Zatarski, M. M., and Nordine, P. C., "Aeroacoustic Levitation: A Method for Containerless Liquid-Phase Processing at High Temperatures," *Review of Scientific Instruments*, Vol. 65, No. 2, 1994, pp. 456–465.

[10]Guigné, J., Koplenko, S., Chin, V., Whelan, S., Barmatz, M., and Jackson, H. W., "Ultrasonic Beam Levitator/Positioner—A New Acoustic Levitating and Positioning Approach," *Microgravity Science and Technology*, Vol. 7, No. 4, 1995, pp. 290–292.

[11]Gagné, J.-M., Babin, F., and Fournier, P., "Fusion et Atomisation par Laser de Matériaux en Condition de Microgravité dans le Système LTS, MPB Technologies," Canadian Space Agency Final Rept., St-Hubert, PQ, Canada, April 1992.

[12]Gagné, J.-M., Babin, F., and Paradis, P.-F., "Discussion des Effets Optiques Créés par une Source Laser sur des Particules en Microgravité," *Spacebound '91*, Canadian Space Agency, Publication SB91-001, April 1991, pp. 289–294.

[13]Gouesbet, G., and Sukhodolsky, A. T., "Opportunity of Investigation of Fluid Interface Instability and Thermocapillary Phenomena in Space," *Proceedings of the 1st International Symposium on Hydromechanics and Heat/Mass Transfer in Microgravity* (Perm, Moscow, Russia), Gordon and Breach, New York, 1991.

[14]Lounis, B., Reichel, J., and Salomon, C., "Laser Cooling of Atoms in Microgravity," *Comptes Rendus Académie de Paris*, t. 316, Série II, 1993, pp. 739–744.

[15]Oran, W. A., and Berge, L. H., "Containerless Melting and Solidification of Materials in an Aerodynamic System," *Review of Scientific Instruments*, Vol. 53, No. 6, 1982, pp. 851–853.

[16]Coutures, J. P., Rifflet, J. C., Billard, D., and Coutures, P., "Contactless Treatments of Liquids in a Large Temperature Range by an Aerodynamic Levitation Device and Laser Heating," *Proceedings of the 6th European Symposium on Material Sciences Under Microgravity Conditions* (Bordeaux, France), European Space Agency, SP-256, Noordvik, 1986, pp. 427–430.

[17]DeVillamil, R., *Hydrodynamics*, E.&F.N. Spon Ltd., London, 1912.

[18]Rush, J. E., Stephens, W. K., and Ethridge, E. C., "Properties of a Constricted-Tube Air-Flow Levitator," *Materials Processing in the Reduced Gravity Environment of Space*, Elsevier, Amsterdam, 1982, pp. 130, 131.

[19]Marchenko, A. V., "Effect of Levitation of Bodies of Revolution in Constrained Flow of Heat Carrier," *Teploenergiteka*, Vol. 24, No. 3, 1977, pp. 51–54.

[20]Shklover, G. G., Korotkov, P. F., and Lokhin, N. I., "An Experimental Investigation of Levitation of a Sphere in a Cylindrical Channel," *Thermal Engineering*, Vol. 29, No. 5, 1982, pp. 279–282.

[21]Granier, B., and Heurtault, S., "Density of Liquid Rare-Earth Sesquioxydes," *Journal of the American Ceramic Society*, Vol. 71, No. 11, 1988, pp. 466–469.

[22]Olivier, M., Simard, L., Audet, L., and Lafférière, A., "Development of the Laser Based R&D Test-Bed System (LTS)," MPB Technologies, Montreal, PQ, Canada, Jan. 1990.

[23]Douy, A., "Centre de Recherches sur la Physique des Hautes Températures," Centre National de la Recherche Scientifique, Orléans, France, Dec. 1994.

[24]Badets, M. C., "Aptitude à la Vitrification sans Nucléation Hétérogène de Liquides de Faibles Viscosité à base d'Alumine, Ph.D. Dissertation, Univ. d'Orléans, Orléans, France, 1991.

[25]Nordine, P. C., Lee, E. H., and Hurd, J. L., "Spectral Emittance of Polycrystalline Alumina," *Revue Internationale des Hautes Températures*, Vol. 17, No. 2, 1980, pp. 165–171.

[26]Massiot, D., Trumeau, D., Touzo, B., Farnan, I., Rifflet, J.-C., Douy, A., and Coutures, J.-P., "Structure and Dynamics of $CaAl_2O_4$ from Liquid to Glass: A High Temperature ^{27}Al NMR Time Resolved Study," *Journal of Physical Chemistry*, Vol. 99, No. 44, 1995, pp. 16,455–16,459.

[27]Coutures, J.-P., Rifflet, J.-C., Florian, P., and Massiot, D., "Étude par Analyse Thermique et par RMN très Haute Température de ^{27}Al de la Solidification de Al_2O_3 en l'Absence de Nucléation Hétérogène: Effets de la Température du Liquide et de la Pression Partielle

d'Oxygène," *Revue Internationale des Hautes Températures et des Réfractaires*, Vol. 29, No. 4, 1994, pp. 123–142.

[28]McAdams, W. H., *Heat Transmission*, McGraw–Hill, New York, 1954, pp. 229, 266.

[29]Weber, J. K. R., and Nordine, P. C., "Containerless Liquid Phase Processing of Ceramic Materials," *Microgravity Science and Technology*, Vol. 7, No. 4, 1995, pp. 279–282.

[30]Heurtault, S., "Étude Théorique et Expérimentale du Refroidissement avec Changement de Phase, à Haute Température, de Particules Sphériques à Propriétés Physiques Variables. Application à l'Alumine," Ph.D. Dissertation, Univ. de Perpignan, Perpignan, France, 1983.

[31]Kingery, W. D., "Surface Tension of Some Liquid Oxides and Their Temperature Coefficients," *Journal of the American Ceramic Society*, Vol. 32, No. 1, 1959, pp. 7–10.

[32]Nelson, L. S., Richardson, N. L., Keil, K., and Skaggs, S. R., "Effects of Oxygen and Argon Atmospheres on Pendant Drops of Aluminum Oxide Melted with Carbon Dioxide Laser Radiation," *High Temperature Science*, Vol. 5, No. 2, 1973, pp. 138–154.

[33]Poe, B. T., McMillan, P. F., Côté, B., Massiot, D., and Coutures, J.-P., "Structure and Dynamics in Calcium Aluminate Liquids: High Temperature ^{27}Al NMR and Raman Spectroscopy," *Journal of the American Ceramic Society*, Vol. 77, No. 7, 1994, pp. 1832–1838.

[34]Incropera, F. P., *Fundamentals of Heat and Mass Transfer*, Wiley, New York, 1990.