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PRELIMINARY EXPERIMENTS ON SURFACE FLOW VISUALIZATION IN THE CRYOGENIC WIND TUNNEL BY USE OF CONDENSING OR FREEZING GASES

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SUMMARY

Users of cryogenic wind tunnels must have available surface flow visualization techniques to satisfy a variety of needs. While the ideal from an aerodynamic stand would be non-intrusive, until an economic technique is developed there will be occasions when the user will be prepared to resort to an intrusive method. One intrusive method is proposed, followed by some preliminary evaluation experiments carried out in environments representative of the cryogenic nitrogen tunnel.

The technique uses substances which are gases at normal temperature and pressure but liquid or solid at cryogenic temperatures. These are deposited on the model in localised regions, the patterns of the deposits and their subsequent melting or evaporation revealing details of the surface flow. The gases were chosen because of the likelihood that they will not permanently contaminate the model or tunnel.

24 gases are identified as possibly suitable and four of these were tested from which it was concluded that surface flow direction can be shown by the method. There is the possibility that other flow details might also be detectable. The cryogenic wind tunnel used for some of the tests was a type insulated on the outside and did not show any signs of contamination.

1. Introduction

Among the several options which exist for visualizing surface flows on models in cryogenic wind tunnels, as yet the use of a frozen deposit of a gas does not seem to have been explored. The notion is that the introduction of a suitable gas to the flow just upstream of the model in the form of a discrete localised jet or jets might, at an appropriate model surface temperature, deposit in the solid phase and show at least some detail of the flow direction adjacent to the surface. There is also the possibility that the nature of the deposition of the solid, or its subsequent reliquefaction or sublimation, might show evidence of other flow properties such as transition, separation or shock position. There is the further possibility that the streaming and evaporation of a deliberately melted solid deposit or of a deposit made in the liquid phase, might show surface flow details. It is recognised that some flow phenomina, transition in particular, might be affected by the presence of the deposit in its solid or liquid phases.

The phrase *'marker gas'* is used loosely in this report to refer to the state, at normal temperature and pressure (NTP), of a substance which is to be used for surface flow visualization. When in use in a cryogenic wind tunnel the marker gas might undergo several changes of phase. The technique is intended for application to the nitrogen cryogenic wind tunnel. These gases are chosen because they combine the possibility of showing surface flow details with the possibility that they will not permanently contaminate the model or tunnel. The intent is that once temperatures are raised sufficiently the deposits will become volatile, vaporise and then be carried away in the nitrogen flow.

Following the identification of possible gases, demonstrations were devised using some gases which happened to be readily available, in order to begin to explore the notion. In one demonstration the gases were simply blown onto the surface of a cooled polished stainless-steel plate in order to view the nature of the deposit, in particular its appearance, its contrast against the metal. The other demonstration involved the injection of the marker gas into the gaseous nitrogen flow in a small cryogenic wind tunnel[1,2], upstream of a flat plate supported in the test section. Although the accumulated experience is limited it has reached the stage where experimental evidence points strongly to the technique being viable. Reporting therefore would be appropriate.

2. Possible marker gases

The search was aimed at listing the commercially available non-toxic gases which have melting temperatures in the relatively arbitrary range 77K to 150K at atmospheric pressure. It should be noted that a quoted temperature applies to melting in the presence of the liquid phase of the same substance. In general the melting (or sublimation) of the solid will be modified in the environment of a wind tunnel where there might exist complex combinations of phases, and gradients of partial pressure of the gas phase adjacent to the surface of the model, possibly modifying the melting and boiling temperatures. The two-dozen gases identified under these guidelines are listed in Table 1 in the order of increasing melting temperature. Included also are the boiling temperatures and their costs in the UK relative to an equal mass of gaseous nitrogen.

The liquid phase of one of these, propane, already has been exploited successfully in surface flow visualization[3-6] in the cryogenic wind tunnel. The liquid propane was used to carry pigment or dye for deposition, the propane subsequently evaporating but, in doing so, persisting long enough to carry a useful distance.

The persistence of a liquid trail might depend not only on the tunnel test conditions and the boiling temperature of the marker gas, but also on the band of temperature over which it remains in the liquid phase. Inspection of the table will reveal that the spread of melting temperatures is fairly even throughout the range, with a good variety of liquid bands. Figure 1 has been prepared to emphasise and summarise these properties.

If the melting or sublimation of a solid deposit does prove to be a useful tool in flow visualization then the choice of the marker gas might be important because the temperature of the phase-change could (although some experiences to be presented later suggest that this may not be the case) become one determinant of the Reynolds number of a test. The values of the Reynolds numbers available in an atmospheric pressure cryogenic nitrogen tunnel with the set of gases have been calculated for Mach 0.1 and are presented in the form of a Reynolds number ratio also in Table 1. This is the ratio of the Reynolds number in the cryogenic wind tunnel to that in a conventional tunnel at the same pressure and Mach number. There are wide variations of pressure around wind tunnel models possibly affecting the temperatures of phase changes, but for the purpose of these computations the stagnation temperature of the tunnel flow is assumed equal to the melting temperature of a substance as given in the table. Similar

computations are possible for other stagnation pressures and Mach numbers, but may be pointless until more experience is gained on the influence of the tunnel environment on the phase-changes. The discrete values of available Reynolds numbers are illustrated on Figure 2. A good spread is evident. If the evaporation of a liquid deposit proves useful then different temperatures and Reynolds numbers apply.

Among these gases the only ones which are listed as corosive are numbers 22 and 24, and in these cases only with copper and silver.

Finally, the point should be made that almost certainly there are more gases which could be considered as evidenced by the experience with carbon dioxide detailed below. For example the fact of a gas having a relatively high freezing temperature does not necessarily mean that it is unsuitable for deposition as a solid on a model at a lower temperature.

3. A simple bench-top demonstration

Four gases were chosen for this initial investigation, the choice being relatively arbitrary but influenced by the information in Table 1 and also their immediate availability. These were carbon dioxide, butane, Freon-12 and argon. The first does not appear in Table 1 because its sublimation temperature does not fall into the cryogenic range, but it was available, is non-toxic and a suspicion existed that it could easily be induced to deposit as a solid. The freezing temperatures of the gases are respectively 194.7, 134.8, 115 and 84K. The CO_2 and argon were stored in commercial compressed gas cylinders, the Freon-12 and butane in small canisters used for an air-brush and a camping heater respectively.

The experimental setup is illustrated on Figure 3. The deposit was formed on a small polished stainless steel plate carrying a thermocouple taped to its front side. The temperatures must be taken as very approximate because of the crudeness of the arrangement for controlling the temperature of the plate. The plate was hung vertically in a cryostat and was cooled initially to 77K by dipping it into liquid nitrogen. Some control could be exercised over the temperature of the plate by withdrawing it from the LN_2 and allowing it to warm in the GN_2 before attempting a deposition. A triple-glazed window excluded the atmosphere. Marker gas was introduced briefly along a pipe as illustrated, the pipe being pre-purged with the gas.

CO_2 was deposited very easily at a plate temperature of about 79K, forming almost instantly a relatively uniform white CO_2 frost layer over the whole plate, which finally sublimed when the plate temperature reached about 190K.

Solid butane deposits were also formed at a plate temperature of about 79K, having the clear appearance of ice rather than a frost. The deposit appeared to melt at about 145K and finally to dry at about 220K. The clear solid deposit did not seem suitable for flow visualization purposes, although the liquid phase might prove useful.

Freon-12 proved easy to deposit in the solid phase. Deposits were produced at various plate temperatures between about 111K and 79K, all with the appearance of a white frost. The solid deposits appeared to begin to melt at an indicated temperature of about 145K and to be completely evaporated at about 230K. In the plate temperature band 230K to 135K the deposits were seen to form as a clear liquid.

In contrast it was not possible to detect any deposit of argon, liquid or solid, despite efforts to form deposits at plate temperatures very close to that of LN_2.

There seemed to be no problem with freezing of the marker gases in the pipe. These results encouraged the following trials in the 0.1m cryogenic wind tunnel.

4. Wind tunnel tests

4.1 The tunnel

As the tunnel has been described elsewhere this section contains only summary information pertinent to the flow visualization tests. The tunnel first ran in 1977 and was constructed for flow visualization work. It is a small continuous running, closed circuit, fan driven tunnel operating at atmospheric stagnation pressure, the big end being vented directly to atmosphere. Cooling is by liquid nitrogen stored in a pressurised cryostat and injected in the downstream direction into the first diffuser. There are electrical heaters for the main stream and also for the fan bearing. Operating temperatures can be varied between about 80K and 380K. The tunnel has thermal insulation only on its outside. The option is available for the automatic control of Mach number and stream stagnation temperature using a microcomputer which also acts as a data logger. The operating envelope in the form of unit Reynolds number as a function of Mach number and temperature is shown on Figure 4. For these tests only a low Mach

number was used close to 0.1 and therefore on this figure the locus of all runs was a narrow vertical line centered at M = 0.1.

4.2 The test section arrangement

The streamwise cross section of the test section is square, nominally 4 inches across (0.1m) with corner fillets. The walls are aluminium and contain an observation window and various types of instrumentation. A door is used for mounting models.

The longitudinal cross section of the arrangement for these tests is shown on Figure 5, a sketch which extends from the end of the contraction to the beginning of the first diffuser. A flat plate representing a model was positioned in the middle of the stream at zero incidence. The plate was 1/16th-inch thick and 3 inches long. The width was 2.4 inches and therefore the edges of the plate were well clear of the walls of the test section. It was mounted on a streamlined support made from a resin impregnated cloth laminate having a low thermal conductivity. A copper-constantan thermocouple was buried in the plate just aft and to one side of the support strut.

The leading edge of the plate was radiused to discourage a separation bubble. The information in hand does not allow a claim that a bubble did not exist, or to speculate on the state of the boundary layer on the plate. The plate was smooth aside from the intrusions of a pair of fixing screws. The more upstream screw can be seen in the photographs of Figure 6. The screws were countersunk but the heads were not filled.

The marker gases were introduced through a 9/64-inch bore brass tube which was positioned as shown on Figure 5 for this operation, directly ahead of the leading edge. The tube was exposed to the cold flow and was uninsulated. It was occasionally traversed away from the leading-edge region after depositing the gas. The supply pipe was primed with the marker gas while the tunnel was still at room temperature, the gas flow then being turned off to avoid plugging the pipe with the marker gas during the cooldown of the tunnel. This risk existed (the event was experienced) largely because the pipe was unheated.

The procedure followed was to cool the tunnel to a desired temperature (and by this stage any air in the tunnel would have been purged) then to briefly inject a marker gas while observing and photographing results thorugh the window. It was found that at steady state the plate and stream temperatures were equal to within

instrument error, ± 2K. Mach number was under continuous closed-loop control but for these tests the temperature control was manual. On the occasions when a phase change was to be induced in a deposit the temperature of the tunnel and plate were allowed to drift upwards with the LN_2 supply turned off. Tunnel tests were carried out with argon, CO_2 and Freon-12. Results are discussed only for the latter two because, as with the bench tests, there were no visible deposits of argon.

4.3 Results

4.3.1 CO_2

Solid deposits were formed in repeated demonstrations as a streak downstream of the pipe at plate temperatures between 163K and 220K. Under the illumination of a tungsten filament lamp their perceived colour was not always white but varied from white through grey to brown depending on the viewing angle. The contrast with the aluminium plate was always good. When the plate was allowed to warm gradually the streak disappeared but not in a uniform manner. There was a tendency for a waisting of the deposit to form just after the leading edge and the deposit to first disappear at the waist, then downstream, then finally between the waist position and the leading edge. The uneven disappearance could have been because of an uneven initial deposit or because of uneven sublimation, or both. In one significant demonstration a streak of solid CO_2 was deposited at a plate temperature of 163K while the tunnel and plate were slowly warming. The deposit had completely cleared by the time the temperature reached 173K. Both of these temperatures are well below the quoted sublimation temperature of CO_2, about 195K. From the accumulated experience it is beginning to appear that CO_2 deposits may be made at any temperature from about 77K to around 200K, and that sublimation will be experienced at stream temperatures well below 195K.

Photographs are shown on Figure 6. The view is directly onto the plate. Its leading edge is identified and the greyness of this edge is caused by its radius. The flow is left to right; the dispensing pipe is just visible but out of focus because it has been retracted to avoid the possibility of the sublimation events being influenced by its wake. The upper photograph was taken just after deposition at a temperature of about 190K. The streak, which is parallel-sided and generally dark in this picture, is visible in the picture for only a short distance. This is a consequence of imperfect illumination. The streak could be seen easily by eye reaching to the trailing edge of the plate. The lower

picture was taken of the same streak at a later time and a temperature of 220K. The streak is somewhat narrower and has almost disappeared in the region indicated by the X, the waist.

In order to begin to test for durability, on one occasion a solid deposit was formed on the plate at 195K following which the tunnel temperature was reduced for a period. The minimum temperature reached was 90K during this run of 42 minutes in the temperature range which cycled from 195K to 90K and then back through 195K to 220K when the streak disappeared. During all but the final moments the streak remained essentially unchanged in appearance.

4.3.2 Freon-12

This marker gas was used during one 1-hour run of the cryogenic wind tunnel and the following comments summarise the principal observations. The minimum temperature reached during the run was 85K. Deposits of liquid or solid F-12 were made in the temperature range 223K to 101K.

Liquid F-12 was deposited several times in the temperature range 223K to 115K during the initial cooldown of the tunnel. The liquid was clear but could be seen easily by eye streaming in the wind. In the narrow temperature range 113K to 101K the deposits were solid, forming a patch extending rearwards from the leading edge. The appearance of the deposit was non-uniform, streaky in places as though the F-12 had formed a slush. If the marker gas was left flowing for some seconds there was a build-up like rime ice on the leading edge, also the formation of solids around the inside and outside of the pipe, The solid deposits were white and clearly visible. On warming the tunnel to about 115K (a figure which agrees very well with Table 1) the deposits melted and streamed away.

In the same manner as for CO_2, an F-12 solid was deposited (at 113K) and the tunnel cycled down to a low temperature and back up again to the melting point. This cycle took 10 minutes during which the minimum temperature reached was 85K. The frozen F-12 remained in place until the first signs of melting at the end of the cycle, at 115K. The whole deposit had melted at 117K.

During the warmup of the tunnel towards the end of the run, liquid F-12 was again deposited. The temperature range explored was 139K to 183K, where of course no problems were caused by the freezing of the gas at the pipe. The deposited liquid

formed a relatively uniformly wetted streak, easily visible. With the marker gas turned off the wet streak dried progressively from the edges of the streak inwards at a rate which seemed to increase with temperature even though this range of temperature is well below that quoted in Table 1 for the boiling of F-12, 243K. The evaporation was presumably a consequence of the low partial pressure of F-12 in the tunnel, but does seem to offer the possibility that the manner of the evaporation might show surface flow details additional to that of flow direction.

5. Discussion

5.1 Impact on the tunnel

As the substances chosen here for flow visualization purposes are non-toxic, do not react with most metals and are well into the gas phase at NTP, there does not seem to be any likelihood of the permanent contamination of the tunnel (or model) or its operators. The gases will disappear from the circuit with the gaseous nitrogen used for cooling. Many are combustible in air but the quantities that are needed for flow visualization purposes are so small in relation to the tunnel flow that they will be regarded only as trace gases in the exhaust flowing from the chimney.

The question of the affinity of marker gases for insulation materials must be addressed in the cases of some tunnels. It could be that such questions might affect the designs of future cryogenic wind tunnels.

5.2 Prospects for visualizing surface flow details

Flow direction. There is no doubt that direction information is available using CO_2 and Freon 12. The direction is shown by frozen or condensed deposits. There is the likelihood that other marker gases will be usable.

Separation. It is likely that leading-edge separation will be apparent from the selective deposition of marker gas and/or its selective removal, the selectivity arising from the differing natures of attached and separated flows. There was some evidence that this occured during tests with CO_2. Indications of separations further aft will depend also on the effective length of travel of deposits from the points of injection of marker gases into the flow.

Transition. It is possible that the different states of the boundary layers will induce either different rates in the sublimation of a solid deposit or, using the technique of slowly raising the temperature of the tunnel stream and the model, the different states might induce melting or evaporation at sufficiently different times to allow transition to be located. The experiments covered by this report showed no evidence to support this suggestion.

Shock position. As in the case of transition the prospects remain speculative at this stage, but the changes in surface flow accompanying a shock might, further along the learning curve, be exploited to indicate position.

5.3 Carbon dioxide

At first sight this marker gas appears to have limited interest for application to the cryogenic wind tunnel because its sublimation temperature is rather high at about 195K. Running a tunnel near this temperature confers only a small advantage in terms of Reynolds number compared with conventional tunnels. However the accumulated experience with the bench-top experiment and the cryogenic tunnel suggests otherwise: deposits of the solid have proved to be possible in the cryogenic tunnel at temperatures well below 195K, and furthermore the appearance of the deposits made to date suggests that they are thin which might be important. One consequence is that the range of candidate gases included in Table 1 might be overly conservative.

5.4 Dispensing the marker gas

It is likely that a heated or alternatively well insulated pipe will be required for dispensing the marker gas, to prevent blockage of the pipe at temperatures below the freezing point, to avoid the formation of slush at somewhat higher temperatures and perhaps to control the temperature of the marker gas to influence the nature of its deposition. Its temperature at injection might influence the length on position of deposits downstream from the point of injection, or the grain size of solid deposits.

Tests with a real model will require either multiple pipes (or nozzles), or a manoeuvrable pipe, or dispensation to orifices from within the model which was practiced with propane[3,4]. This might prove restrictive because it is unlikely that a model could be heated close to surface orifices to avoid freezing.

5.5 Future testing

This is likely to be a substantial operation in view of the range of candidate marker gases which exists coupled with the other unexplored matters which include:

design of gas dispenser;
search for methods for showing the flow details of separation, transition and shock location;
rates of sublimation below the freezing point;
tunnel internal insulation;
effect of model material and surface finish;
effects of tunnel pressure and Mach number;
measurement of deposit sizes;
effect of temperature of marker gas.

An investigation of the size and variety implied will require considerable effort and, logically, the use of small cryogenic wind tunnels including a pressure tunnel in order to establish the best methods for application to the large low speed and the large transonic pressure tunnels. As scale effects may be important, ultimately it will be necessary to prove the methods in the large scale tunnels.

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Table 1. A range of gaseous substances at NTP which melt in the temperature range 77 to 150K (under the liquid phase at 1 atmosphere)

	Substance	Temperatures, K.		Relative Cost	Reynolds nr. ratio	Formula
		Melting	Boiling			
1	Propane	83.3	231.1	3.9	5.75	C_3H_8
2	Argon	84	87.3	0.7	5.67	A
3	1-Butene	87.8	266.9	18	5.3	C_4H_8
4	Propylene	88	225.5	1.8	5.29	C_3H_6
5	Methane	89	111.7	30	5.2	CH_4
6	Freon 14	89	145.2	23	5.2	CF_4
7	Freon 13	92	191.7	7.5	4.94	$CClF_3$
8	Ethane	101.2	184.5	8.1	4.29	C_2H_6
9	Ethylene	103.8	169.4	2.8	4.13	C_2H_4
10	Krypton	104	119.8	220	4.12	Kr
11	3-Methylbutene-1	104.7	293.6	26	4.08	C_5H_{10}
12	Freon 22	113	232.4	2.6	3.64	$CHClF_2$
13	Freon 12	115	243.4	0.6	3.55	CCl_2F_2
14	Freon 23	118.2	191.1	6.2	3.41	CHF_3
15	Isobutane	128	261.4	4.5	3.04	C_4H_{10}
16	Freon 13 B1	129.9	215.4	9.8	2.98	$CBrF_3$
17	Isobutylene	132.8	266.3	1	2.88	C_4H_8
18	Xenon	133	164.8	2200	2.88	X
19	cis-2-Butene	134.3	276.9	24	2.84	C_4H_8
20	Ethylchloride	134.4	285.4	5.4	2.84	C_2H_5Cl
21	Butane	134.8	272.7	5	2.82	C_4H_{10}
22	Allene	137.2	238.7	110	2.75	C_3H_4
23	Freon 21	138.2	282.1	3.5	2.72	$CHCl_2F$
24	Ethylacetylene	143.2	281.9	35	2.59	C_4H_6

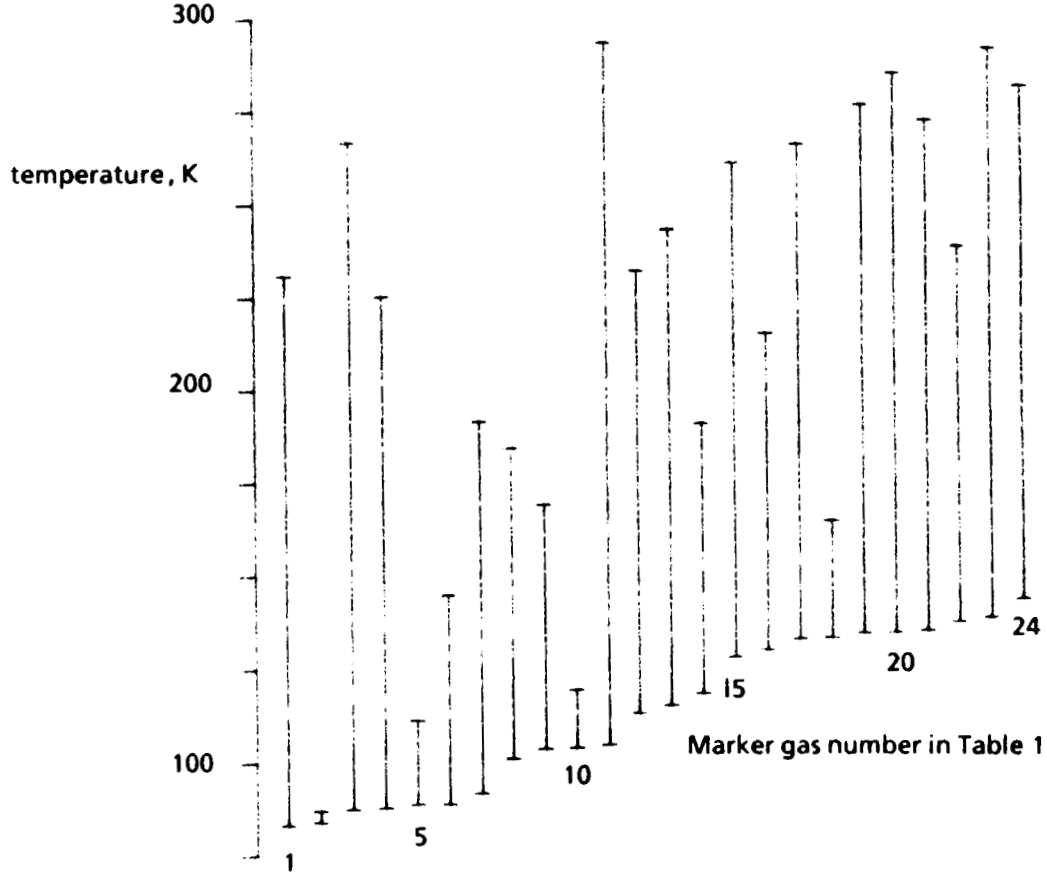

Figure 1. Illustration of the melting temperatures in the range 77 to 150K available with non-toxic substances, with the bands over which they remain liquid.

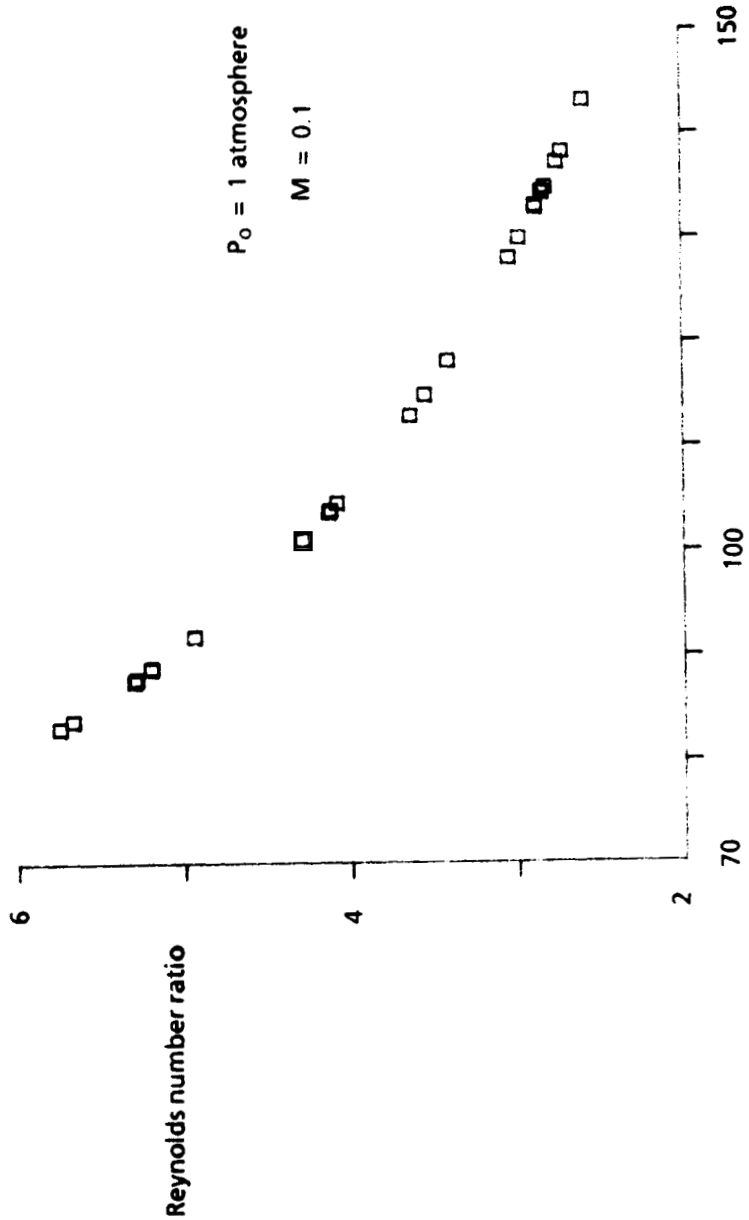

Figure 2. The discrete values obtainable of the ratio of Reynolds number at melting point T_{MP} to that at 288K, using the gases listed in Table 1.

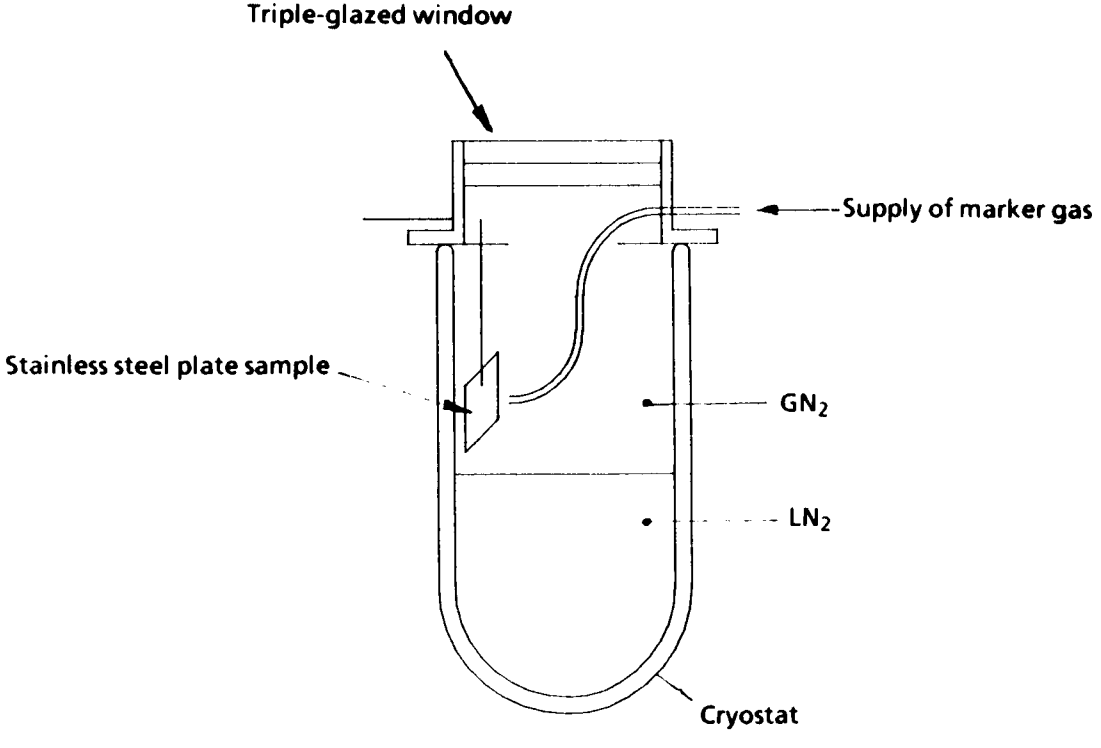

Figure 3. Bench-top equipment for demonstration of the deposition of marker gases.

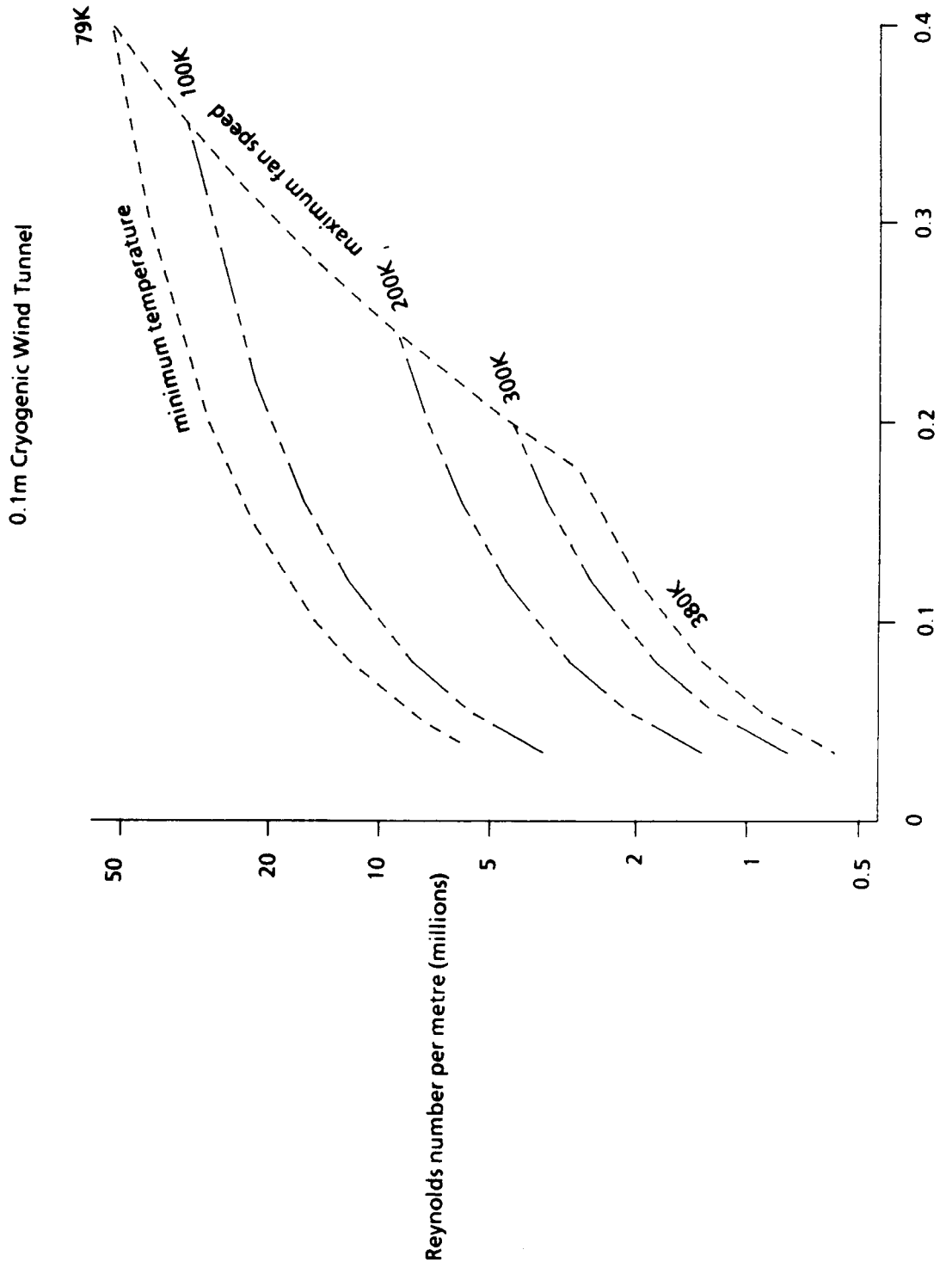

Figure 4. Operating envelope.

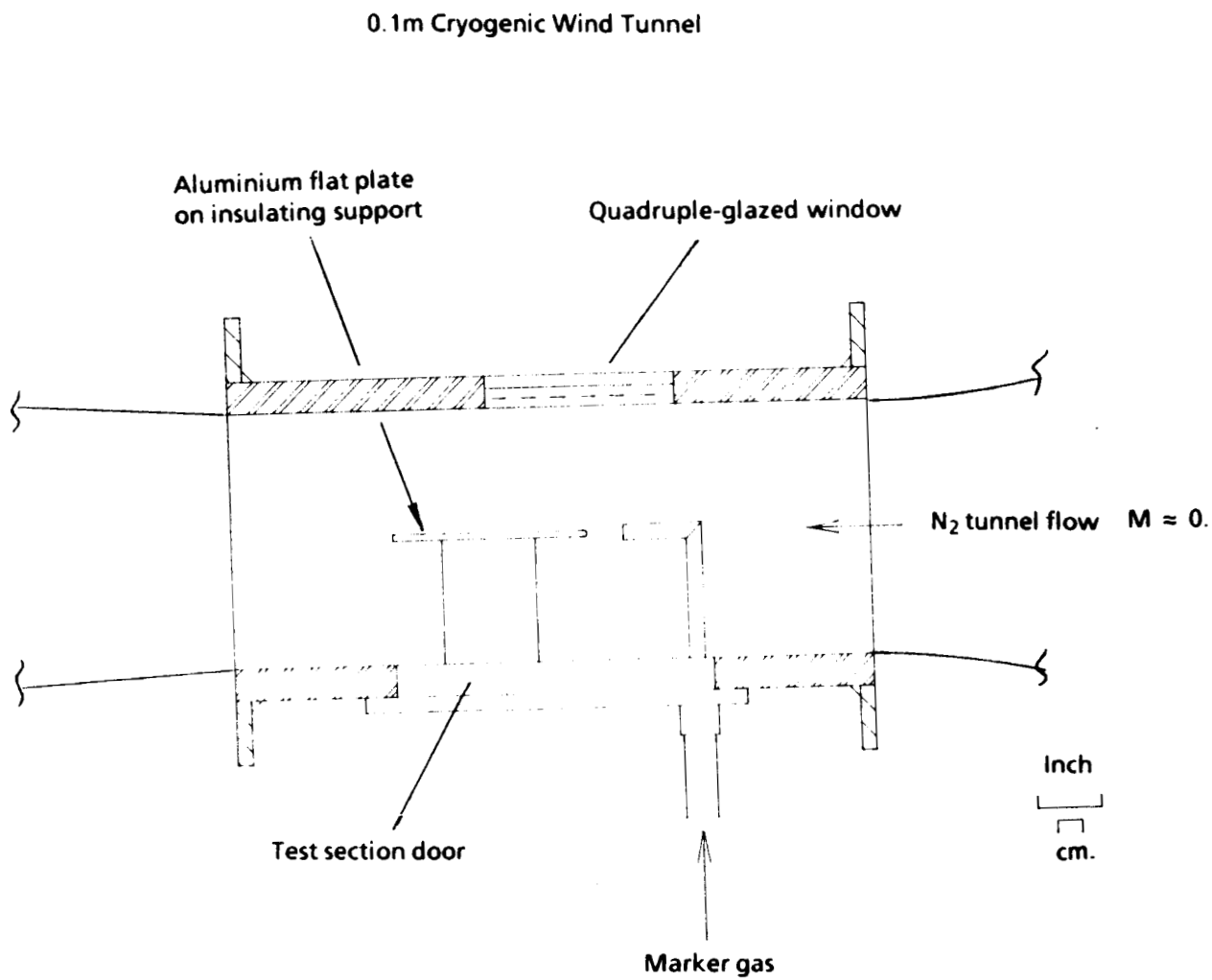

Figure 5. Arrangement of surface flow visualization demonstrations using deposits of condensing or freezing gases in a cryogenic wind tunnel.

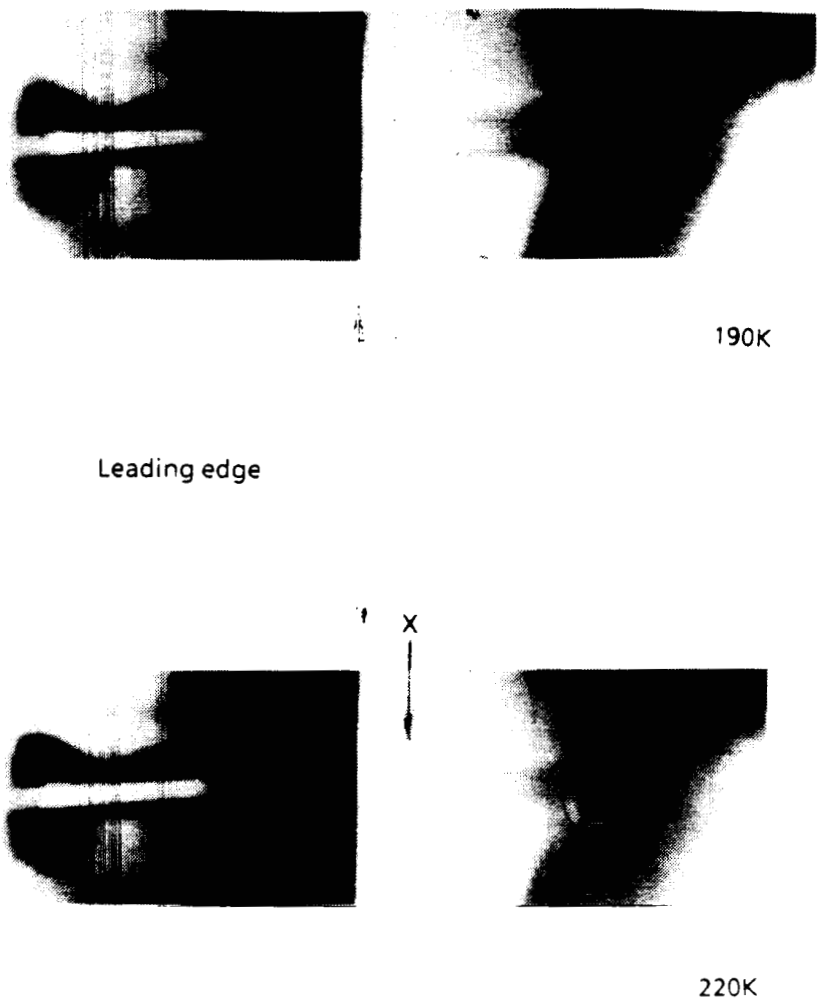

Figure 6. Photographs of solid CO_2 shortly after deposition (upper) and later showing partial sublimation (lower).

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16. Abstract

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