Two-phase liquid-gas cooling for silicon PIXEL detectors

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Abstract

One proposed cooling technology for silicon detectors is based on the use of the latent heat of vaporization of the following selected fluids: water, saturated fluorocarbons and ammonia. A two-phase liquid-gas test bench will be described. Saturated vapour pressure mesurements and temperature distributions along a single silicon ladder (Pyrex channel) cooled with "fluorinert" FC-72 will be presented.

Heat-pipe performence tests have been carried out within the two following configurations: at first stand alone and then integrated onto heated silicon wafers.

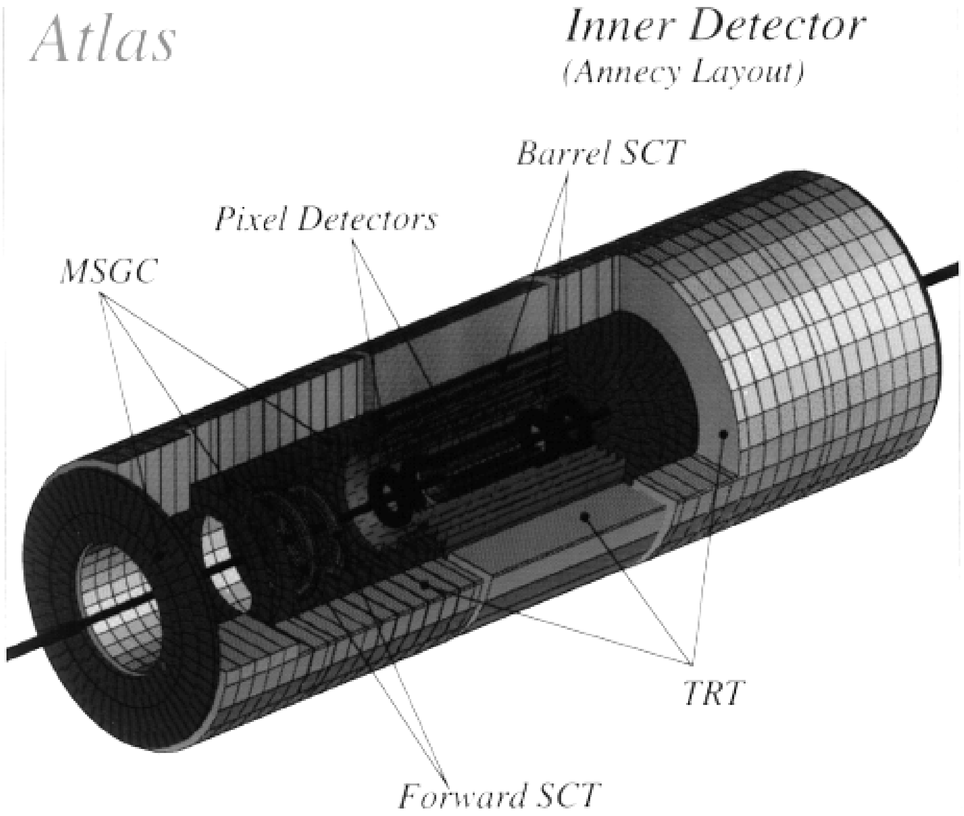


Fig (1) General view of ATLAS inner detector (length = 6.5m, diameter = 2.14 m)

1. Introduction

Silicon detectors have been proposed for use in the inner tracker [fig (1)] of the ATLAS experiment[1] for the high luminosity (L = 10^{34} cm^{-2} s^{-1}) LHC collider at CERN. The innermost tracking layers (at radii 11.5 and 16.5 cm) will be implemented in a pixel geometry best suited to the high multiplicity environment close to the beams. However these detectors must operate in a very high radiation environment[3]: the inner layer is expected to receive radiation damage equivalent to a dose of about 2.5 MRad [or $8.3.10^{13}$ 1 MeV neutrons cm^{-2}] per LHC "year" (of 10^7 seconds operation).

Figure (2) shows a pixel detector module. A silicon tile with implanted pixel detector diodes carries an array of flip-chip bonded readout chips (each of area $1cm^2$) to process the pixel signals. The thermal dissipation of this electronics is expected to be 0.4 Wcm^{-2}. The pixel detector operating temperature must be maintained close to 0°C, with a temperature variation of no more than ± 2.5°C over the silicon detector surface. To avoid condensation, the detector volume will be flushed with dry nitrogen at a temperature around 0°C.

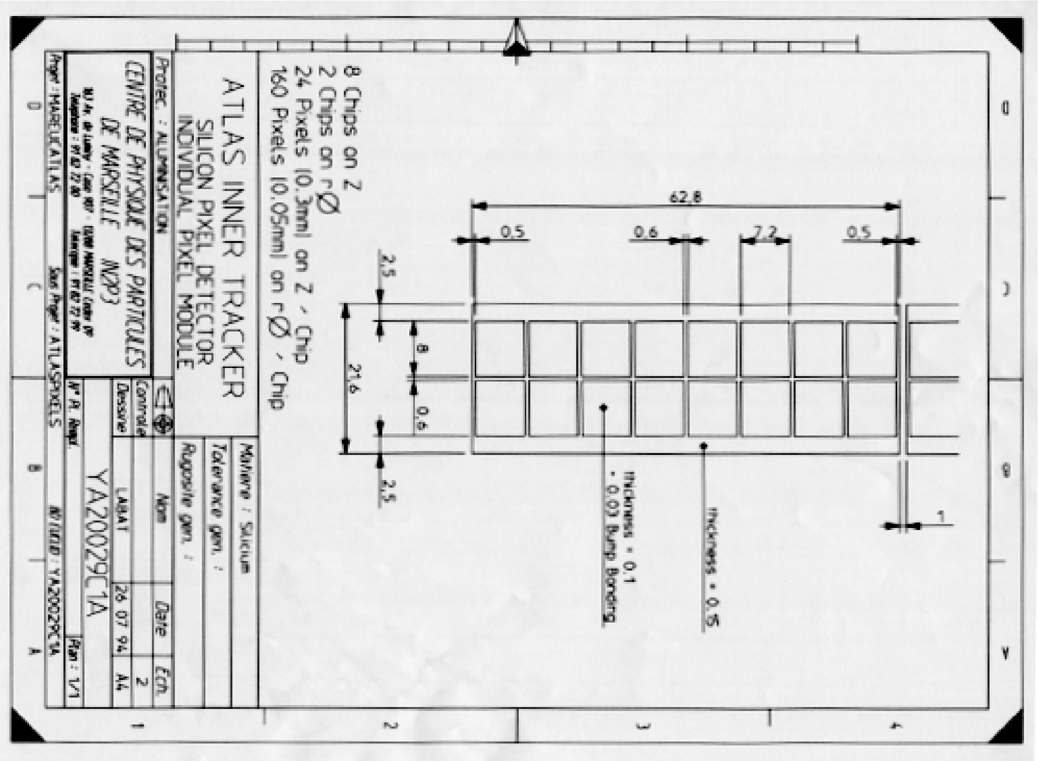


Fig (2) Pixel detector module: pixel diodes are implanted in the silicon substrate to which two rows of electronic readout chips are flip-chip bonded

2. Mechanical Structure

The proposed mechanical support structure (under study at CPPM) is shown in fig (3). It has several components:

- layer support cylinders consisting of a single 0.4 mm beryllium skin over most of their lengths - reinforced at each end with two more 0.4 mm beryllium braces, and divided axially into two demicocques for access to the detector modules - carrying aluminium inserts for the attachment of detector ladder supports;

- axial detector ladder supports (aligned parallel to the LHC beam), consisting of pairs of thin aluminium cooling channels (0.15 mm wall), carrying spring clip attachments for individual silicon detector tiles [fig (4)];

- a cooling fluid recirculation system under development.

Such a structure has several advantages:

(i) a very high rigidity to mass ratio through the use of cylinders in beryllium (Young's modulus = 340000 Nmm^{-2}, density = 1.85 gcm^{-3});

(ii) a high degree of modularity with both the axial support / cooling ladders and the silicon detector modules individually demountable [fig (4)];

(iii) lightness, through combination of support and cooling functions in the same structure, minimizing the multiple scattering of particles crossing the detector [table (1)];

(iv) low cost (relative to an all - beryllium structure) through the use of thin extruded aluminium cooling channels. A brazed aluminium-beryllium overall assembly is envisioned.

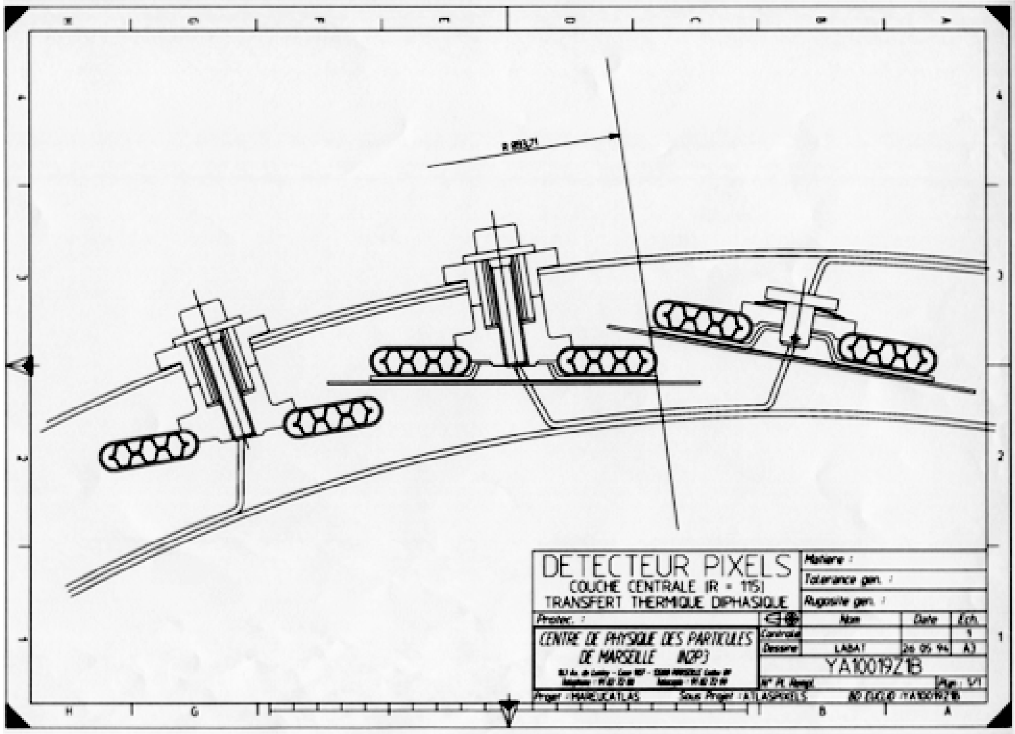


Fig (3) Cross sectional view of the detector support cylinder, showing the mounting of detector ladders

Layer Radius (mm)	z position (mm)	Total % X/X0	Description
115/125	0/350.4	(0.92 + 0.12) = 1.04	1st layer pixel tiles (inc detectors. electronics. cabling & cooling) + Be support shell
130	350/450	(0.24 + 0.32 + 0.30) = 0.86	Shell reinforcement + 1st layer cooling + cabling
125/175	450	(0.24 + 0.28 + 0.26) = 0.78	Radial Support +1st layer cooling + cabling
165/175	0/414.2	(0.92 + 0.12) = 1.04	2ndlayer pixel tiles (inc detectors. electronics. cabling & cooling) + Be support shell
180	414.2/450	(0.24 + 0.32 + 0.3) = 0.86	Shell reinforcement. 2nd layer cooling & cabling
175/225	450	(0.24 + 0.50 + 0.47) = 1.21	Radial Support 1st & 2nd layers cooling & cabling
225	0/860	0.36	Main support and attachment cylinder

Table (1) Material distribution (in % radiation lengths at normal incidence) for the pixel layers and support structure.

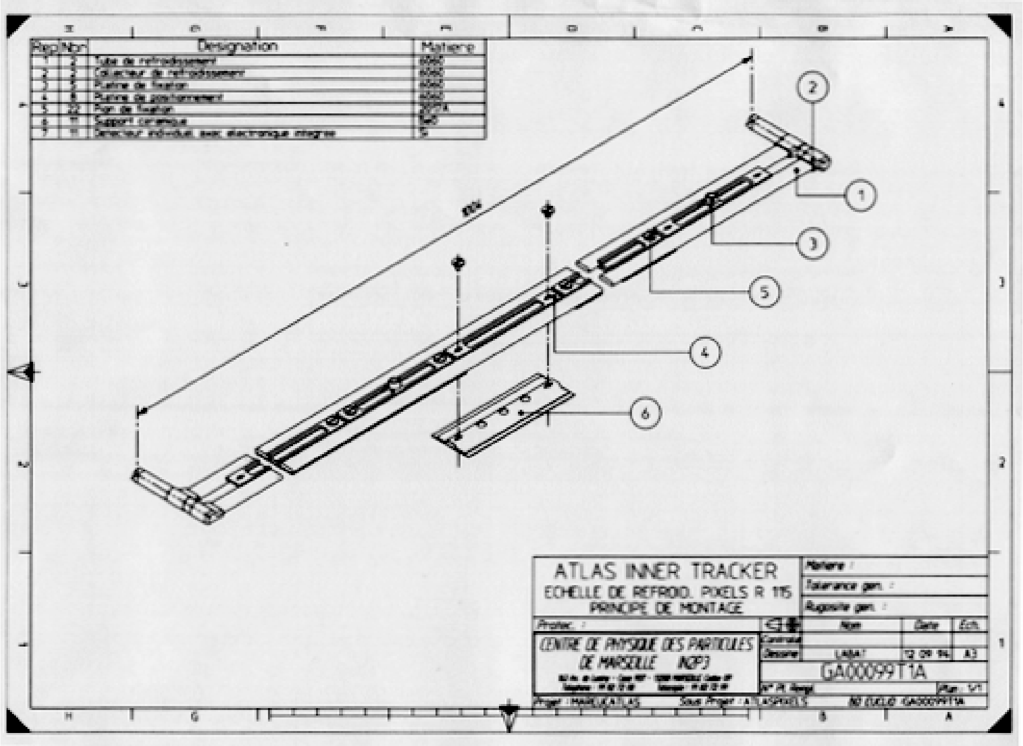


Fig (4) Ladder support showing the two cooling channels and the mounting points for pixel detector modules

3. The Cooling System

Table (2) shows the thermal characteristics of the pixel layers at 11.5 and 16.5 cm.

The cooling system for these detector layers must;

(i) evacuate around 6 kW of dissipated heat from the detector to external heat exchangers, which will probably be situated 30-50 m away, outside the experimental area;

(ii) maintain a temperature gradient of no more than ± 2.5°C over the entire detection surface (1.4m^2 in area) about the operating temperature of 0°C;

(iii) induce minimal vibration (both in amplitude and frequency) into the structure - from either mechanical (pumps etc) or thermal (cyclic expansion) effects;

(iv) be leak-tight to a high degree to avoid contaminating the detectors with leaking refrigerants, or a failure of cooling in part of the detector.

Layer Radius	No Ladders	No modules / ladder	No modules total	Active area/ ladder (cm^2)	Total active area (cm^2)	Power diss./ ladder (W)	Total power diss. (W)
115	48	11	528	112.86	5417	45.2	2170
165	64	13	832	133.38	8536	53.4	3418
Both layers			1360		13953		5588

Table (2) Thermal characteristics of the pixel layers at 11.5 and 16.5 cm

At CPPM, we are studying evaporative cooling systems in which heat is removed by the latent heat of vaporization. Studies have been made of two different types of systems:

(a) an open, pumped, system using an evaporating flourocarbon [2] [3M "fluorinert" liquid: product designation FC72-

predominantly perfluoro-hexane: (C_6F_{14})] ;

(b) a network of completely closed individual "heat pipe" systems, containing water.

	Boiling Temp (°C) (1 ATM)	Density (g/cm^3)	Viscosity (dyn. cs)	Vapour pressure at 25°C (mbar)	Heat Capacity (J/g°C)	Latent Heat of vaporiz. (J/g)	Therm. Conductiv. (W/m°C)	Surface Tension (10^{-5} N/cm)
Water	100	1.0	1.0	32	4.2	2257	0.58	72
FC-87	30	1.63	0.4	813	1.05	100.5	0.056	12
FC-72	56	1.68	0.4	308	1.05	90	0.057	12
Ammonia	-33	0.68	0.14	10.000	2.06	1370	0.47	20

Table 3: Physical properties of selected refrigerants

Both systems make use of a liquid-gas biphase flow, with the saturated vapour pressure at the point of liquid evaporation controlling the temperature, and with the amount of heat that can be removed being directly proportional to refrigerant liquid flow into the evaporator.

The planned evaporator consists of the network of aluminum cooling tubes in parallel arranged around the detector layers. with a pair for each ladder of detectors [figs (3,4)]. The tubes contain capillaries to help maintain a thin film of liquid in contact with the tube wall. in which the liquid - vapour phase change is driven by the heat absorbed from the electronics. A good match of the capillary mesh pore size to the surface tension of the chosen refrigerant should allow the formation of a stable and uniform fluid film.

3.1 The Prototype Evaporator

Figure (6a,b) shows the prototype (single tube) evaporator, in which have started to study cooling with FC72 refirgerant. A cylindrical capillary mesh (50mm pore size, 80 mm pitch) is inserted inside a pyrex tube of 4 mm internal diameter. The FC72 refrigerant enters at one end of the tube, entrained as an aerosol mist in a flow of dry nitrogen carrier gas. The mist impinges on the wick, and FC72 liquid preferentially moves along the inner surface of the tube by capillarity, while the nitrogen passes through the centre of the tube. The exhaust mixture of nitrogen and vapour evolved from the tube walls is evacuated with a pump. The pressure in the tube is measured with an electronic pressure gauge.

The use of a nitrogen carrier confers several advantages (§3.3);

- easier control of the pressure in the cooling channels via the equilibrium between the pumping speed and the combined supply speed of the nitrogen and evolving refrigerant vapour;
- more uniform wetting of the capillary mesh and more uniform observed temperature gradient along the tube.

In one of the pair of cooling channels per detector ladder [fig(4)], the massflow, m_l, of evaporative liquid refrigerant necessary to remove the dissipated heat, P_{ec} , is given by;

$$\boxed{m_l = \frac{1/2P_{ec}}{h_l}} \qquad \text{Eqn (1)}$$

where h_l ,is the latent heat of vaporization of the liquid. As an example, a ladder dissipating 60 Watts and cooled by evaporation of FC72 (h_l =90 J/g)will require a liquid mass flow of 0.34 g/s

From knowledge of the geometry of the capillary mesh and the tube, it is possible to calculate the thickness and linear flow velocity of the liquid film along the interior of the tube. In the case of the prototype evaporator tube, we estimate that the minimum space beteen the mesh and the inner surface of the tube is 0.1 mm.

The maximum liquid laminar flow velocity, u_l, is given by

$$u_l = m_l \;/\; (A_l.\rho_l) \qquad \text{Eqn (2)}$$

where $\mathbf{A_l}$ is the cross sectional area of the liquid film, and $\rho_\mathbf{l}$ is the liquid density.

In the example above, for the prototype tube, the FC72 maximum flow velocity would be around 0.16 m/s.

At the tube exit, assuming that all the liquid supplied has been vaporized, the vapour volume flow, $\mathbf{q_V}$, is given by

$$q_{V.} = m_l \;/\; \rho_V \qquad \text{Eqn (3)}$$

where $\rho_\mathbf{V}$ is the vapour density. In the example above, for the prototype tube, the FC72 vapour flow rate is around 15 cm^3/s, with a corresponding linear (laminar) flow rate (for a 4mm internal diameter tube), $\mathbf{u_V}$, around 1.2 m/s.

3.2. Condenser

In the proposed system, the nitrogen carrier gas will be vented, while the refrigerant may be recondensed for recirculation. Recondensed refrigerant will held in a reservoir, and will be pumped back to the evaporators in liquid form at ambient temperature.

3.3. Observed temperature regulation in the prototype evaporator

Around an operation point of 0°C, we were able to see that a small change in the flow of injected nitrogen was sufficient to vary the temperature profile along the tube. Several mechanisms could be responsible for this:

- a variation in the equilibrium (total) pressure in the cooling tube. The variation of attainable temperature with pressure in pure FC72 is shown in fig (5);
- a change in the dynamics of the phase transition: the evacuation of the evolving FC72 vapour, or in the geometry of the liquid film on the interior of the tube;
- a variation in the forced convection in the tube, and consequently in the heat transfer characteristic.

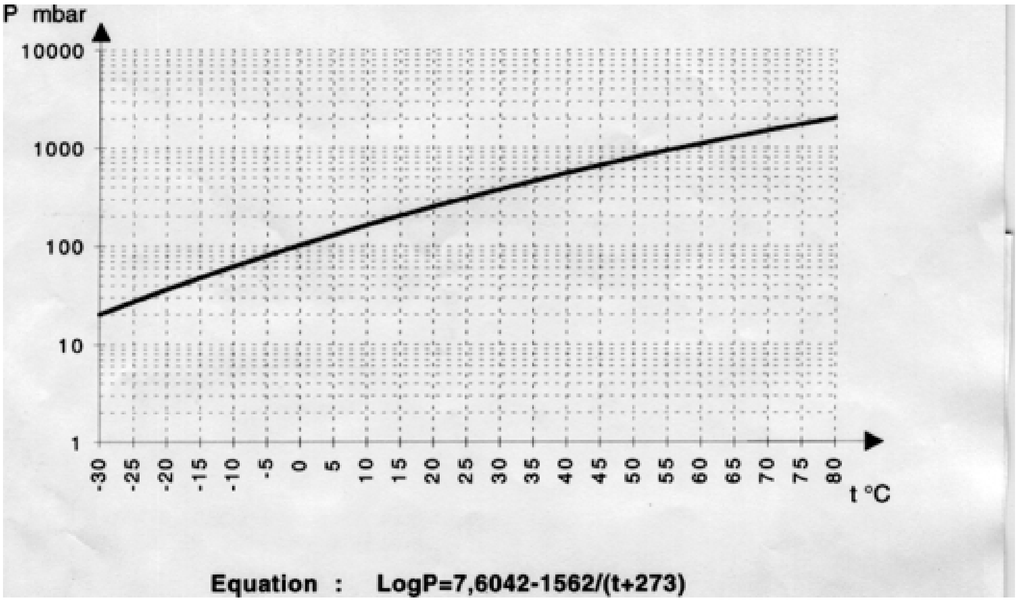


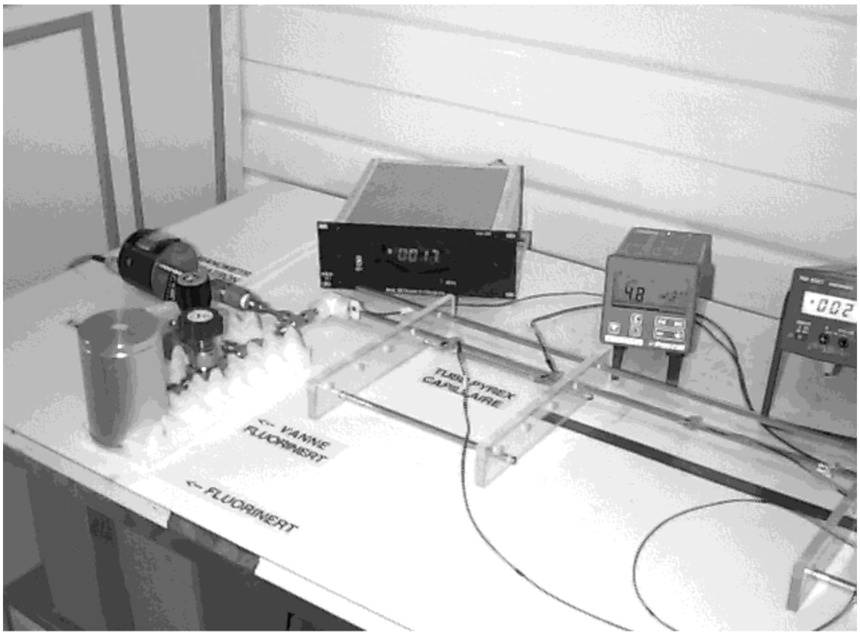
Fig (5) Vapor Pressure Curve for fluorinert FC72

The addition of a stable, low flow of nitrogen gas into the cooling tube allowed us to obtain (in the test tube) a temperature gradient that was stable in time. The heat source in our preliminary test was just the temperature difference between ambient room air at 27°C and the cooled tube. A big change in the thermal load to be evacuated will require an adjustment of the amount of liquid refrigerant injected into the system. To be sure that sufficient liquid is being injected it is advisable to tune the system so that a small amount of liquid is present at the output. The liquid presence could be verified by (for example) a small immersed resistive element, which could be used to control the flow of liquid at the injection point. A small flow of liquid at the exit should not impede the bi-phase cooling performance of the system. An ultrasonic (speed of sound) gas analyzer cell installed in the exhaust of the array of cooling tubes can provide a very accurate measure of the relative concentrations of FC72 (C_6F_{14}) vapour and nitrogen in the exhaust mixture: in conjunction with the known input nitrogen flow rate, this can indicate the amount of power being removed by the cooling system. Such analyzers have been demonstrated to provide a mixture measurement accurate to 1 part in 10^4 for FC87 (C_5F_{12}) vapour / nitrogen mixtures [7].

3.4. Performance Summary

We have found in preliminary studies with the cooling system of §(3.1): [figs (6a,b)]:

- a temperature variation of ±1.25°C along the length of the 750 mm test cooling tube when operated at a temperature of 0°C [at a corresponding (total) tube input pressure of 75 torr (99 mbar)]; the total pressure established with the aid of a slow flow of nitrogen gas [fig (7)];
- a temperature variation of ±1.9°C along the length of the 750 mm test cooling tube when operated at a temperature near 5°C [corresponding tube input pressure of 97 torr (128 mbar)], with slow nitrogen flow;
- that the thickness of the capillary film in the tube is of the order of 100 μm, a factor of 10-20 thinner than the material presented by an all liquid cooling system;
- that the capillary liquid film operates in a regime of laminar flow, so that vibrations introduced by a cooling system of this type are expected to be insignificant. We plan, however, to make vibration studies using a laser interferometer to be sure of this.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