Session 7 - Heat Transfer Measurements

SURFACE TEMPERATURE MEASUREMENTS BY USE OF LIQUID CRYSTALS

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1. INTRODUCTION

New improvements in the performance of aero-engines require a detailed and rigorous optimization of their design. In the area of high pressure turbines, the development and validation of computer programs allowing a very accurate prediction of the metal temperature are of crucial importance in order to guarantee the life time of the blades and the endwalls. The definition of accurate and representative test cases dealing with the aero/thermal performances of the different turbine components therefore remains a major task [1, 2]; it is the principal motivation for the work presented in this contribution.

The classical way to improve the thermal efficiency of a gas turbine cycle is to increase the turbine entry temperature. The present engines mostly operate at gas temperatures much higher than the metal melting temperature. They therefore require efficient cooling schemes. One of the first techniques applied to cool turbine blades was internal convection. The coolant air is introduced through the hub section into the blade interior and, following complicated serpentine passages, is blown out through the trailing edge. This method is still heavily used, in combination with film and impingement cooling. A more efficient design of those internal passages therefore requires a deeper understanding of the thermal and aerodynamic phenomena developing in such flows. This is even more critical when remembering that these internal passage surfaces are roughened with different types of ribs to enhance convective heat transfer.

A detailed investigation on a two-pass flow passage with a 180 degree sharp turn bend was therefore initiated. This configuration is quite similar to the one used by a number of previous investigators [e.g. 3-9]. As previously mentioned, the main objective of this work is to perform, on this known configuration, convective heat transfer measurements as accurate and as detailed as possible in order to provide a completely documented test case for this type of flow. The effect of freestream Reynolds number and the effect of ribs on the surfaces of the channel are eventually considered.

The wall temperature measurements are performed with the help of liquid crystals. The specific objective of the present contribution is to present the implementation of the measurement technique. The latter was developed a few years ago at the Japan Atomic Research Institute by Akino et al [10].

2. HEAT TRANSFER MEASURING METHOD

A steady state measuring method has been selected [11]. It permits determination of local heat transfer coefficients by making use of a composite of an electrical heating element and a liquid crystal coated sheet. This kind of "sandwich" is then bonded to the test surface of the channel. A heat balance and measurements of the electrical input to the heating layer (subtracting all the possible losses) are used in conjunction with the air temperature (local or passage-averaged) and the temperature pattern indicated by the liquid crystal layer to provide a measure of the local heat transfer coefficient as well as of its distribution.

If $\dot{q}_w$ is the heat generated per unit area, the local heat transfer coefficient h is defined as follows :

$$h = \frac{\dot{q}_w}{T_w - T_a}$$

T_w and T_a being respectively the wall and air temperatures.

A more detailed description of the elements of the measurement system is given in the following sections.

3. TESTING SURFACE - HEATING ELEMENT

The 180 degree-turn channel walls (Fig. 1) are manufactured from 15 mm thick transparent plexiglass plates and assembled with bolts. A rectangular cross section has been selected; its aspect ratio is 0.5 (width = 2 * height). The air flow is aspirated through the test section at atmospheric pressure and room temperature by means of a small blower. The velocity along the central axis of the channel exit section is measured with the help of a small Pitot probe. Two small type T thermocouples are also installed along the central axis of the entrance and exit sections of the channel. Detailed local air temperature measurements are performed by means of a miniature type K thermocouple probe, surveying several cross sections along the flow path.

The heating element (Fig. 2) is made of a 0.025 mm thick Inconel 600 foil. Inconel is a low resistivity steel (0.0041 ohm /m^2 at 20° C) made of 80 % Ni, 14 % Cr and 6 % Fe. Copper bus bars are specially soldered at both ends of the foil over the entire width to provide a uniform distribution of electrical current over the foil. Both DC and AC power supplies have been used in experiments. The foil is carefully bonded to the bottom surface of the channel by means of a 0.125 mm thick double sided adhesive sheet. A thermochromatics liquid crystal coated polyester sheet is finally glued on top of the heating element. In order to verify the wall temperature distribution obtained by means of the liquid crystals, 15 type T thermocouple junctions are located beneath the Inconel sheet; 5 other junctions are installed under the bottom plexiglass plate in order to evaluate the heat conduction losses through the latter. Independent guard heaters (based on the same operating principle) are located along the side walls of the channel to compensate for lateral conduction losses. The temperature distribution uniformity over the bottom surface is checked before starting the blower. The measurements are performed for a surface temperature of 45 ... 50°C.

4. LIQUID CRYSTALS

Liquid crystals have been known for about one century. Their existence was reported for the first time in 1888 by F. Reinitzer, who observed colour changes of cholesterol esters and noted optical activity under certain conditions. He discovered the existence of two melting points. The first is characterized by the transformation of the substance from a solid to a cloudy liquid. The second is characterized by the change of this cloudy liquid into a transparent one. Mechanically these substances resemble liquids with viscosities ranging from rather low values to almost solid glass; optically they exhibit many of the properties of crystals. For example, a liquid crystal substance scatters light in symmetrical patterns and reflects different colours depending on the angle from which it is viewed.

Much work related to the structure of liquid crystals has been carried out. They are currently classified into three specific categories : smectic, nematic and cholesteric, depending upon their molecular structure. A detailed description of these three classes is presented in [12]. Recently a number of investigators have reexamined in detail the practical uses of these materials. They have pointed out a number of possible applications, arising from the ability of liquid crystals to register fluctuations in temperature, mechanical stress, electromagnetic radiation and chemical environment by changing their colour. The application for temperature change detection is especially interesting for heat transfer measurements. As they are gradually heated, cholesteric liquid crystals will progressively exhibit all colours of the visible spectrum. The phenomenon is reversible and repeatable. A careful calibration relates colours and temperatures in a unique way.

Liquid crystals are commercially available for temperature levels ranging from about -30°C to about 250°C. The temperature span over which all the colours of the visible spectrum are displayed ranges from 1° C to values as large as 50°C. For this particular investigation, encapsulated cholesteric liquid crystals with a span of 5°C were used.

5. WALL TEMPERATURE MEASUREMENT WITH LIQUID CRYSTALS

The use of liquid crystals as a qualitative visualization technique is very impressive: the complete wall temperature distribution is displayed at once. A quantitative determination is, however, more difficult to perform. A method excluding human sensation as well as the lack of reproducibility of colour image techniques must be used. An elegant approach was proposed in 1989 by Akino et al [10, 13, 14].

This method is based on the determination of different isothermal lines for one single heating condition of the test surface. A number of optical filters defined by sharp bandpass characteristics are used to extract isochromatic regions from a liquid crystal coated surface illuminated by an ordinary light source with a continuous spectrum.

The light scattered by the liquid crystals has a given spectral distribution. The intensity of the light, recorded through one of the bandpass filters by a black and white camera, will therefore depend upon the temperature of the liquid crystal and the transmittance function of the selected filter. This intensity will exhibit a maximum for that wavelength of the scattered light (corresponding to a well defined, unique temperature of the liquid crystals) coinciding with the wavelength at which the transmittance function of the selected filter is maximum. The corresponding liquid crystal temperature can therefore be associated with this filter; it is called the peak intensity temperature.

When observing an illuminated liquid crystal layer through the different filters, the maximum intensity recorded by the black and white camera is observed at the location where the surface temperature is equal to the peak intensity temperature. Isothermal lines on the wall can then be defined using the surface temperature at each location.

The peak intensity temperatures have to be determined from a calibration test. Sixteen filters are used in the present application. Their characteristics are summarized in Table 1.

6. LIQUID CRYSTAL CALIBRATION PROCEDURE

The peak intensity temperature is determined for each bandpass filter through a calibration test. This test is performed with the help of the apparatus described in Fig. 3.

A sample of the liquid crystal coated polyester sheet to be calibrated is glued on an aluminium plate; the temperature distribution along the latter is controlled by means of two independent resistive heating elements, fixed at both ends. A stable and almost linear temperature gradient (T_{max} - T_{min} = 5° C) is established over a length ranging from less than 10 mm up to 265 mm and measured by means of nine type T thermocouples buried in the aluminium plate, just under its surface. The complete apparatus is enclosed inside of a sealed plexiglass box. The box is evacuated to a very low pressure to limit as much as possible free convection and gas conduction heat transfer phenomena.

The test plate is illuminated by means of two voltage-stabilized tungsten halogen lamps, installed at such an angle to limit specular reflection from the plexiglass within the area viewed by the camera. The colour distribution displayed by the liquid crystals is observed, through each bandpass filter, by means of a black and white CCD camera located 700 mm above the test plate. With the liquid crystals used in the present investigation, the complete visible spectrum is observed for temperatures ranging from 39°C to 47°C. The different camera signals, corresponding to the different filters, are recorded. The images are then digitized and analyzed by means of an image processor to determine the location of the pixel line exhibiting the maximum intensity (peak intensity). Figure 4 shows the raw intensity distributions (on a scale ranging from 0 (black) to 256 (white)) obtained for the different bandpass filters. The temperature (peak intensity temperature) existing at the location corresponding to these maxima is determined by interpolating the thermocouple data.

The final relationship existing between the center wavelength of the bandpass filters and the corresponding peak intensity temperature is presented in figure 5. This experiment was repeated several times for two different temperature gradients. Both calibrations agree within 0.15°C along the major part of the curve. The present results were also compared to those obtained by Akino et al [10]. A very good agreement was found.

7. APPLICATION TO THE FLOW IN A 180 DEGREE-TURN CHANNEL

An example of measurement within the model presented in section 3 is now very briefly described. The mainstream Reynolds number, based on the hydraulic diameter of the channel, is 20.000.

Typical images recorded through filters with center wavelengths of 530 nm and 660 nm are presented in figures 6 a and b. Combining the information obtained from the images recorded through all 16 bandpass filters with the calibration curve presented in figure 5, the wall iso-temperature lines of figure 7 have been obtained. The uncertainty of the wall temperatures, based on a 20:1 confidence interval, is estimated to be of the order of 0.25°C at this stage of the investigation.

Among other flow characteristics, the expected recirculation bubble, along the central wall at the exit of the bend, is clearly observed. Detailed local flow temperature measurements are still underway to express these data in terms of heat transfer coefficient or Stanton number correlations with Reynolds number.

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FILTER	WAVELENGTH (nm)	BANDWIDTH (nm)
1	441.6	1.0
2	488.0	1.0
3	514.5	1.0
4	530.0	8.5
5	550.0	9.2
6	568.2	1.0
7	590.0	10.0
8	610.0	10.3
9	632.8	1.0
10	647.1	1.0
11	660.0	11.6
12	676.4	1.0
13	694.3	1.0
14	710.0	12.4
15	740.0	13.1
16	770.0	10.8

TABLE 1 : CHARACTERISTICS OF THE OPTICAL FILTERS

The bandwidth is defined as the width of the transmittance function at 50 % of its maximum.

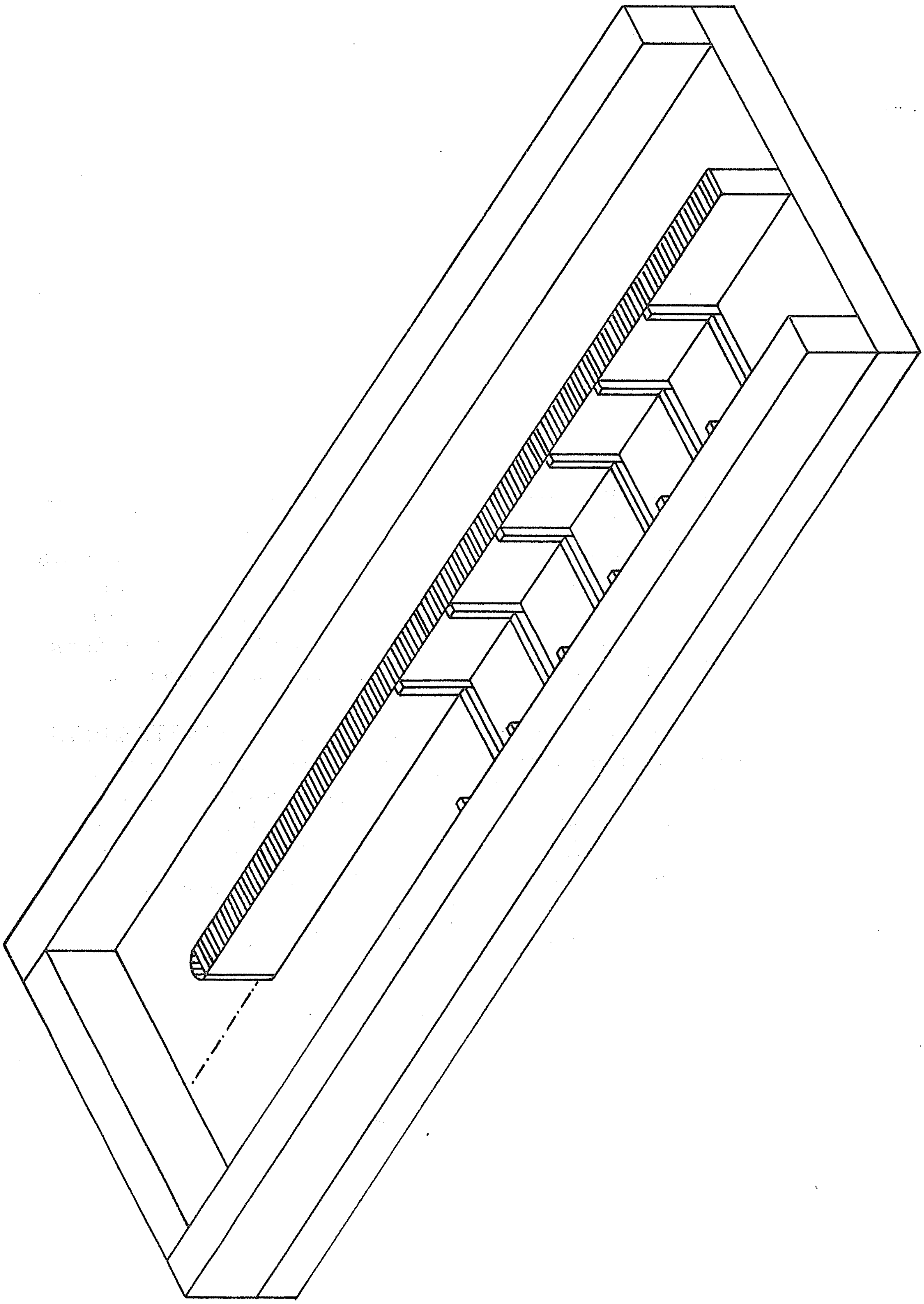

FIGURE 1 - 180 DEGREE-TURN CHANNEL

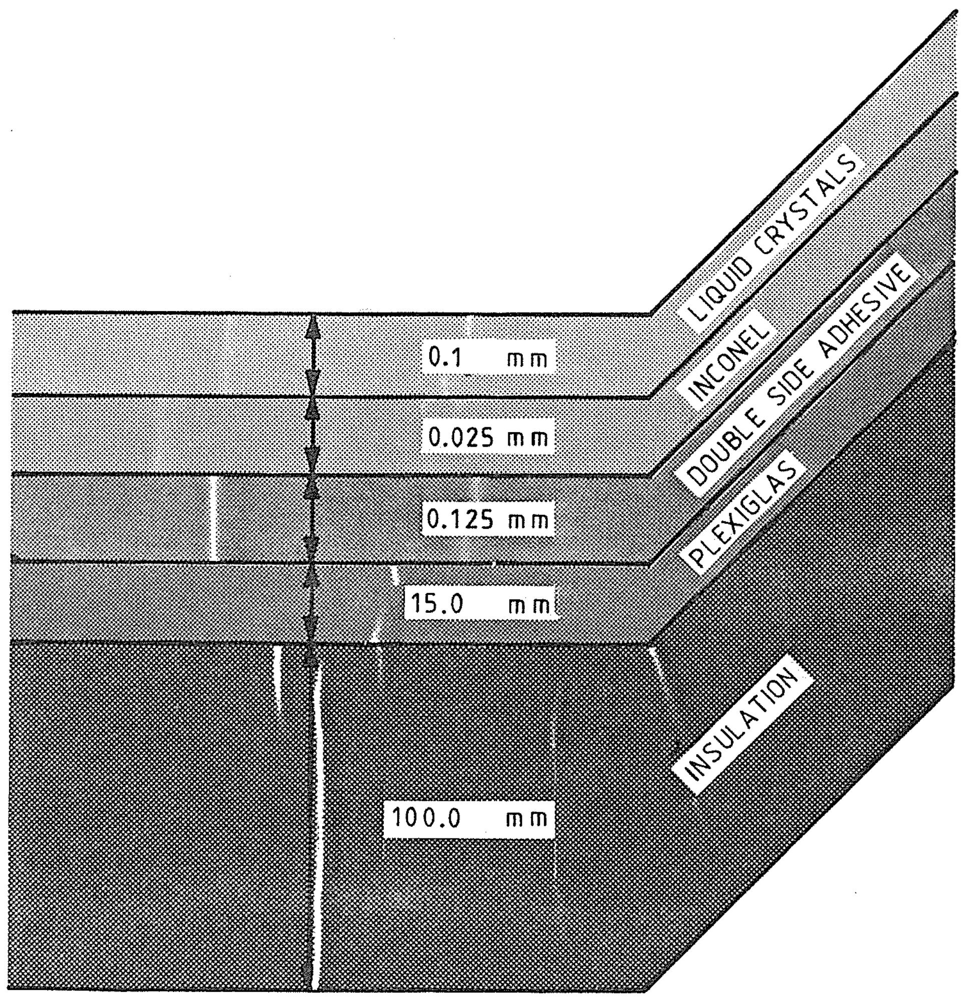

FIGURE 2 - HEATING ELEMENT FOR CONSTANT HEAT FLUX SURFACE

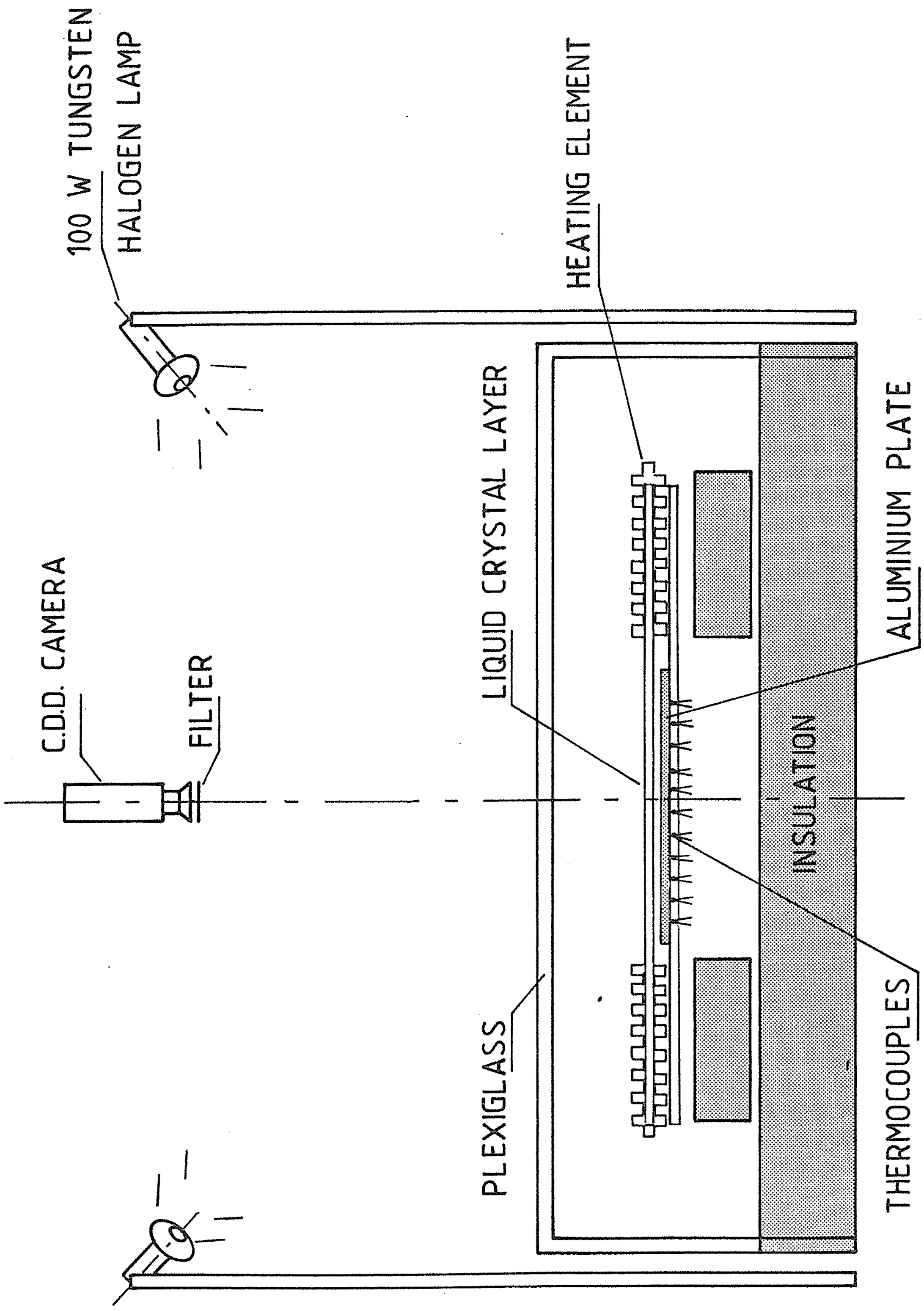

FIGURE 3 - CALIBRATION APPARATUS

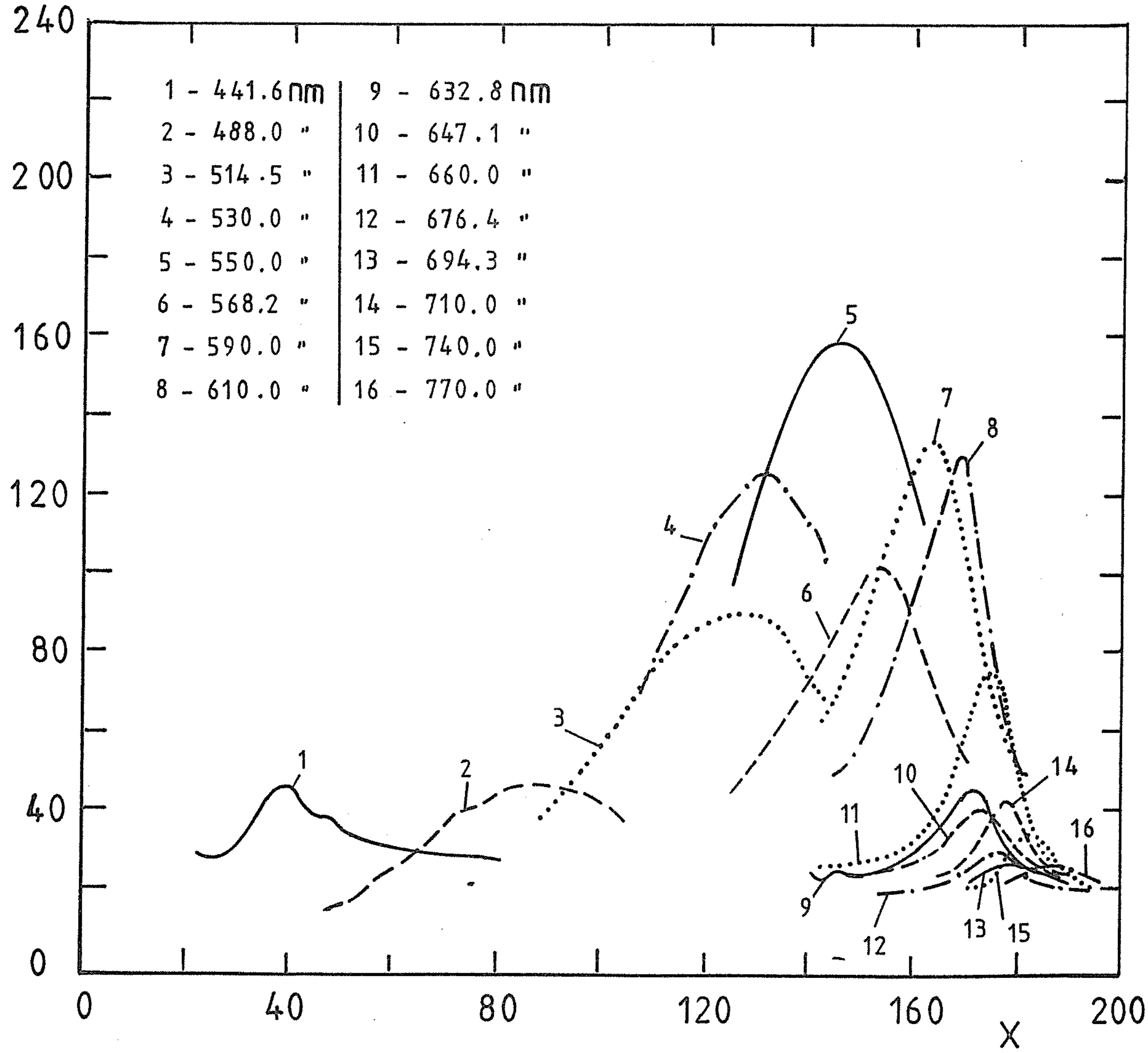

FIGURE 4 - CALIBRATION RESULTS
RAW INTENSITY DISTRIBUTIONS FROM THE BANDPASS FILTERS

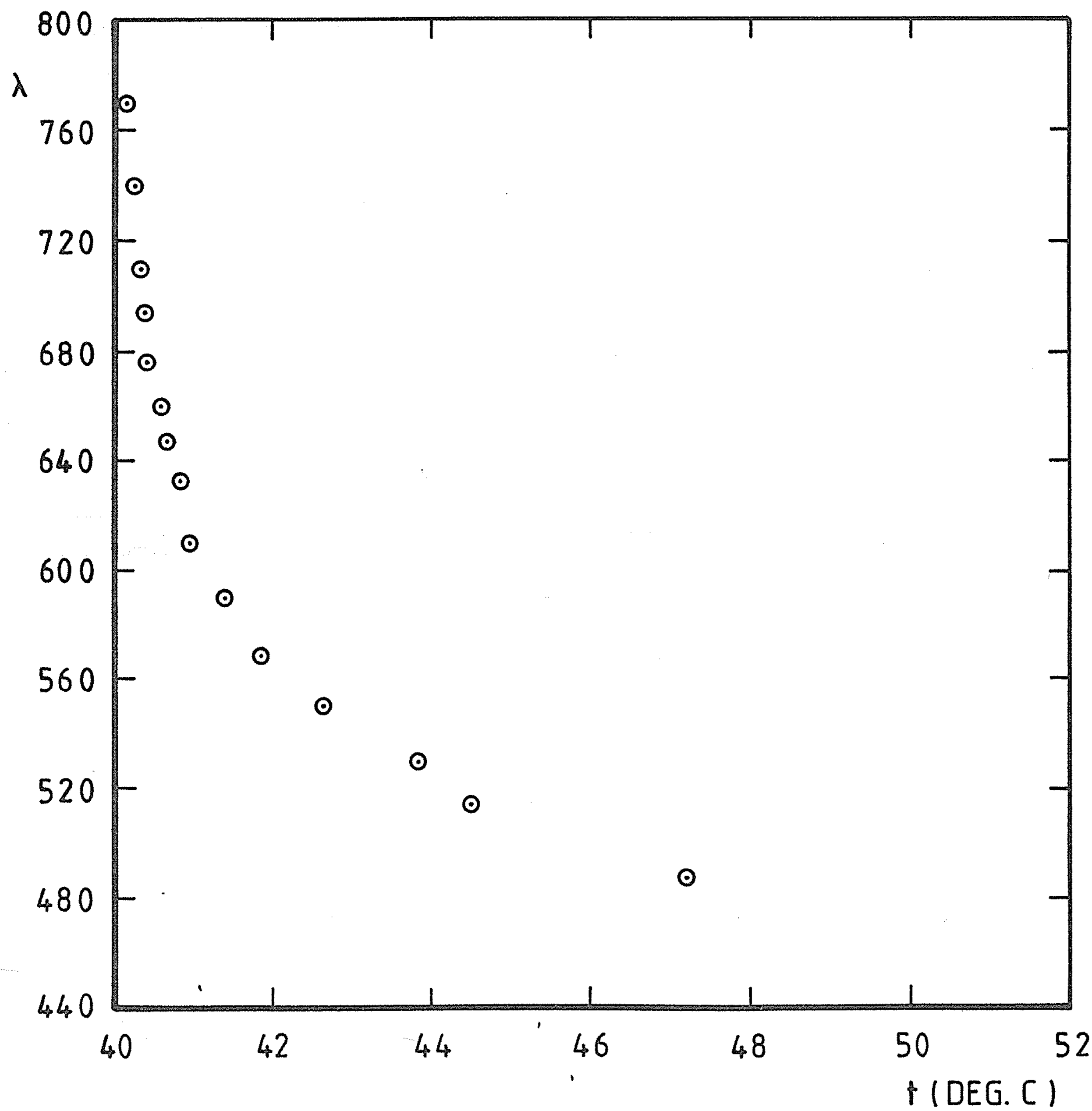

FIGURE 5 - RELATIONSHIP BETWEEN FILTER WAVELENGTH AND PEAK INTENSITY TEMPERATURE

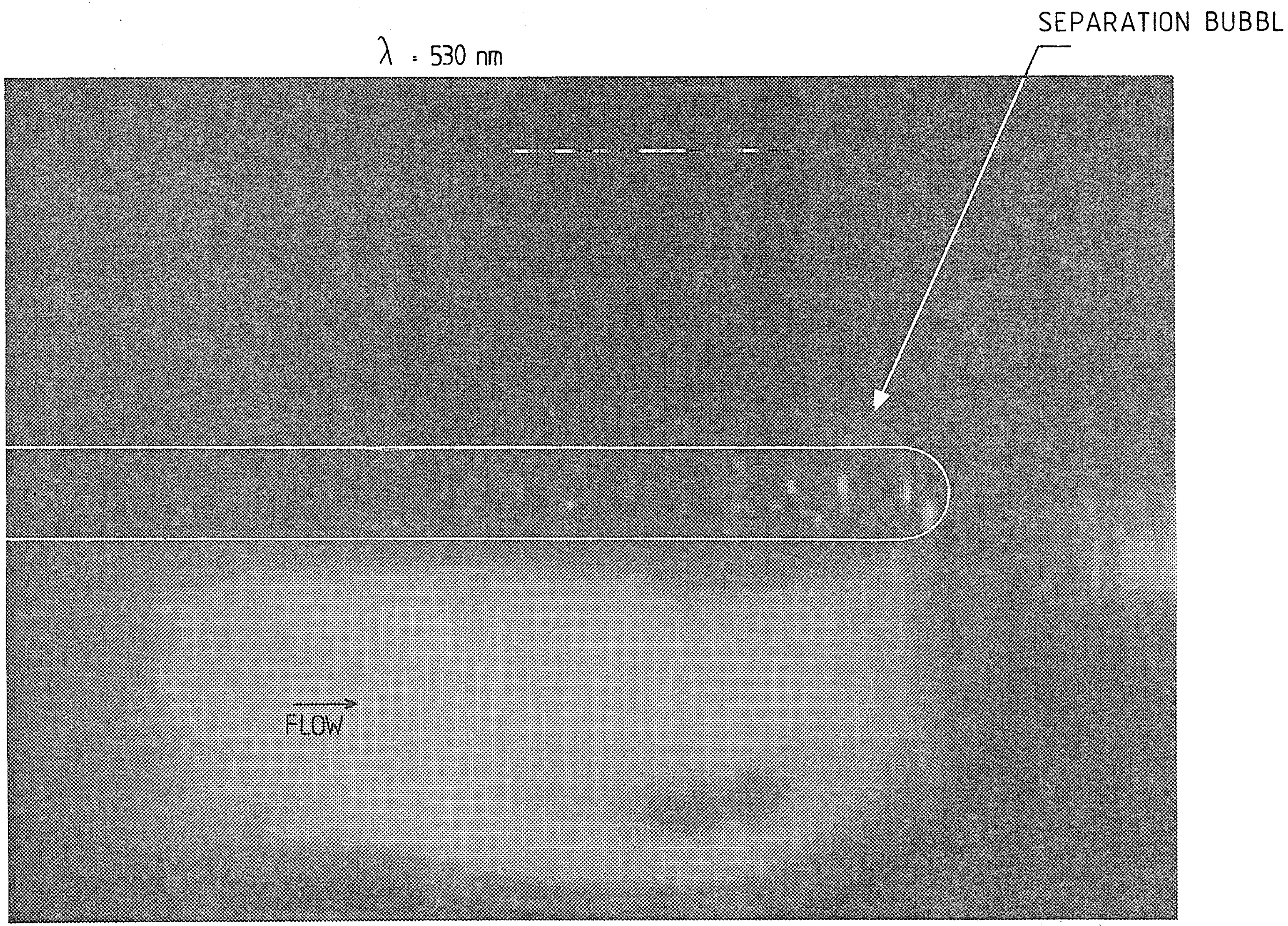

FIGURE 6a - 180 DEGREE-TURN CHANNEL FLOW
IMAGE THROUGH THE 530 nm BANDPASS FILTER

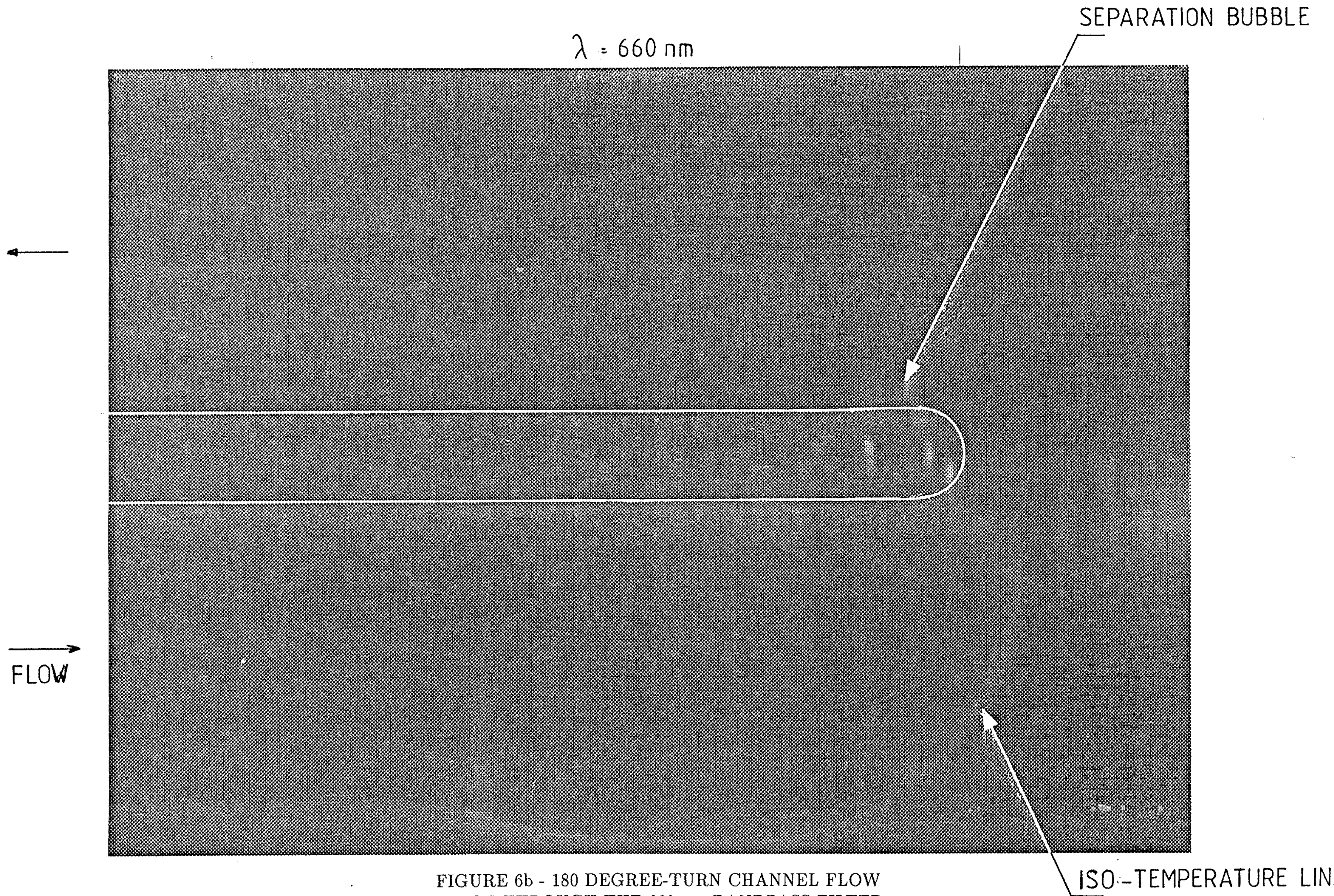

FIGURE 6b - 180 DEGREE-TURN CHANNEL FLOW
IMAGE THROUGH THE 660 nm BANDPASS FILTER

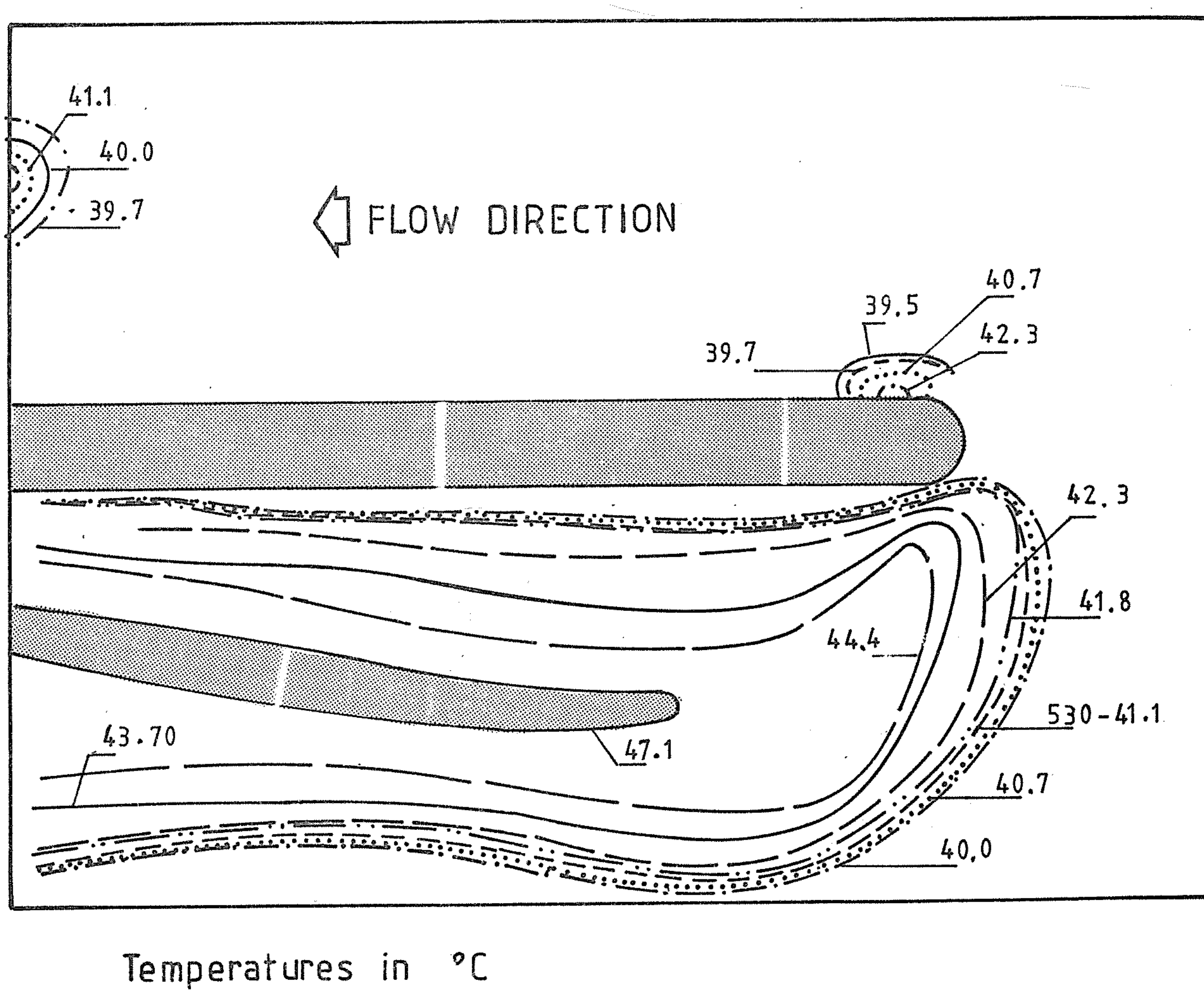

FIGURE 7 - 180 DEGREE-TURN CHANNEL FLOW
TYPICAL ISO-TEMPERATURE LINES PATTERN