JAERI-M
85-008

TEST RESULTS OF THE HOT GAS DUCTS OF HENDEL

February 1985

Kazuhiko KUNITOMI, Ikuo IOKA, Kohji UMENISHI,
Makoto HISHIDA, Toshiyuki TANAKA,
Hiroaki SHIMOMURA and Konomo SANOKAWA

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-Mレポートは，日本原子力研究所が不定期に公刊している研究報告書です。

入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319-11茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319-11茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　刷　㈱高野高速印刷

Test Results of the Hot Gas Ducts of HENDEL

Kazuhiko KUNITOMI, Ikuo IOKA, Kohji UMUNISHI, Makoto HISHIDA
Toshiyuki TANAKA, Hiroaki SHIMOMURA and Konomo SANOKAWA

Department of High Temperature Engineering
Tokai Research Establishment, JAERI

(Received January 11, 1985)

The hot gas ducts A and B of HENDEL, whose completion is in March, 1982, are installed in Adapter section. The hot gas duct A of 15 m in length connects the second-stage He gas heater H_{32} and the first-stage He gas cooler C_{31}. Thermal performance tests of hot gas ducts have been carried out in the preliminary and six cycle operations since March, 1982. By measuring temperatures of the pressure tube and internal thermal insulation as well as heat flux distributions at the surface of the duct, an experimental correlation of the effective thermal conductivity of internal insulation, was obtained. Heat loss from the hot gas duct was measured by means of heat flux meters.

In order to check the experimental results, especially the effective thermal conductivity obtained by heat flux meters, supplemental tests were conducted with a modified hot gas duct A, which was previously cooled by natural convection of air and changed to be cooled by forced convection of air, because heat loss from the hot gas duct was easily calculated by the temperature rise and flow rate of cooling air.

This measurement was applied to the tests conducted in No. 7 ~ 9 cycle operations of HENDEL, from March to July, 1984.

This report describes the results.

Keywords : High-temperature, Gas-cooled Reactor, Helium Gas Loop,
Hot Gas Duct, Pressure Tube, Thermal Insulation,
Effective Thermal Conductivity, Heat Flux

HENDEL高温配管特性試験結果報告

日本原子力研究所東海研究所高温工学部
国富　一彦・井岡　郁夫・梅西　浩二・菱田　　誠
田中　利幸・下村　寛昭・佐野川好母

（１９８５年1月１１日受理）

大型構造機器実証試験ループ（HENDEL）には，耐圧管の内側に繊維系断熱材の層を設けた高温配管が設置してある。この配管の断熱性能を把握することを目的として，昭和５７年度から実施したHENDELの検収試験およびNo.1～No.6サイクルの運転では耐圧管表面温度，熱流束等の計測を行ってきた。この熱流束の計測には薄膜の熱流束計を用いてきたが，昭和５９年５月～７月にかけて行ったNo.７～No.９サイクルの運転では，さらに詳細な熱流束を計測するために，耐圧管の周囲に空冷ダクトを設置し耐圧管表面を強制冷却することにより耐圧管表面からの放散熱量を求めた。

本報は，冷却ダクト試験装置の概要について述べると共に，No.７～No.９サイクルの運転の試験結果をまとめたものである。

Contents

目　　次

1. Introduction

In order to check the experimental results, especially the effective thermal conductivity of the internal thermal insulation layer obtained by heat flux meters in the previous tests, supplemental tests were conducted with the modified hot gas duct A. The cooling method of the hot gas duct A was changed from natural convection of air to forced convection of air. This modification makes it possible to measure heat loss from the hot gas duct by temperature rise and flow rate of cooling air.
During No. 7 - 9 cycle operations of HENDEL, from March to July, 1984, thermal performance tests of the modified hot gas duct A were carried out, and the test results were compared with the previous data.

2. Objectives

Objectives of the tests of the hot gas duct A with the air-cooling channel, are as follows:

(1) Measurement of effective thermal conductivity by the air-cooling method

(2) Comparison of the effective thermal conductivities obtained by the previous and present tests

(3) The effect of He gas pressure on the effective thermal conductivity of internal insulation layer

3. Test apparatus

A test apparatus consists of an air supply system, an air-cooling channel and a measuring system. A flow sheet of the test apparatus is shown in Fig. 1 and the main items in Table 1.

3.1 Air supply system

The air supply system consists of a 7.5 kW blower, air piping, valves and orifice flow meters. The blower supplies air of atmospheric pressure at the maximum flow rate of 30 Nm^3/min.
Air flows in four pipes which are connected to the air-cooling channel. Each pipe has a flow control valve and an orifice meter.

1. Introduction

In order to check the experimental results, especially the effective thermal conductivity of the internal thermal insulation layer obtained by heat flux meters in the previous tests, supplemental tests were conducted with the modified hot gas duct A. The cooling method of the hot gas duct A was changed from natural convection of air to forced convection of air. This modification makes it possible to measure heat loss from the hot gas duct by temperature rise and flow rate of cooling air.
During No. 7 - 9 cycle operations of HENDEL, from March to July, 1984, thermal performance tests of the modified hot gas duct A were carried out, and the test results were compared with the previous data.

2. Objectives

Objectives of the tests of the hot gas duct A with the air-cooling channel, are as follows:

(1) Measurement of effective thermal conductivity by the air-cooling method

(2) Comparison of the effective thermal conductivities obtained by the previous and present tests

(3) The effect of He gas pressure on the effective thermal conductivity of internal insulation layer

3. Test apparatus

A test apparatus consists of an air supply system, an air-cooling channel and a measuring system. A flow sheet of the test apparatus is shown in Fig. 1 and the main items in Table 1.

3.1 Air supply system

The air supply system consists of a 7.5 kW blower, air piping, valves and orifice flow meters. The blower supplies air of atmospheric pressure at the maximum flow rate of 30 Nm^3/min.
Air flows in four pipes which are connected to the air-cooling channel. Each pipe has a flow control valve and an orifice meter.

1. Introduction

In order to check the experimental results, especially the effective thermal conductivity of the internal thermal insulation layer obtained by heat flux meters in the previous tests, supplemental tests were conducted with the modified hot gas duct A. The cooling method of the hot gas duct A was changed from natural convection of air to forced convection of air. This modification makes it possible to measure heat loss from the hot gas duct by temperature rise and flow rate of cooling air.
During No. 7 - 9 cycle operations of HENDEL, from March to July, 1984, thermal performance tests of the modified hot gas duct A were carried out, and the test results were compared with the previous data.

2. Objectives

Objectives of the tests of the hot gas duct A with the air-cooling channel, are as follows:

(1) Measurement of effective thermal conductivity by the air-cooling method
(2) Comparison of the effective thermal conductivities obtained by the previous and present tests
(3) The effect of He gas pressure on the effective thermal conductivity of internal insulation layer

3. Test apparatus

A test apparatus consists of an air supply system, an air-cooling channel and a measuring system. A flow sheet of the test apparatus is shown in Fig. 1 and the main items in Table 1.

3.1 Air supply system

The air supply system consists of a 7.5 kW blower, air piping, valves and orifice flow meters. The blower supplies air of atmospheric pressure at the maximum flow rate of 30 Nm^3/min.
Air flows in four pipes which are connected to the air-cooling channel. Each pipe has a flow control valve and an orifice meter.

3.2 Air-cooling channel

The hot gas ducts A and B were of single tube type with natural air-cooling. The cooling method of the half of hot gas duct A, however, was changed to forced air-cooling. Figure 2 shows the modified hot gas duct A with four subchannels which consists of a first elbow, a vertical tube, a second elbow and a horizontal tube. The cross-sectional view of air-cooling channel is shown in Fig. 3. The air-cooling subchannels surround the outside of pressure tube of hot gas duct. Each subchannel is isolated by separating plates. Flow rate of each subchannel is controlled individually by the control valve. Heat loss from hot gas duct to each subchannel is calculated from temperature rise and flow rate of cooling air. In order to prevent heat loss from air-cooling channel to the atmosphere, the air-cooling channel is covered with thermal insulation.

3.3 Measuring system

(1) Temperature measurement

Temperature of air is measured at mixing headers which are installed at the end of each subchannel. At the outlet of each mixing header, twenty thermocouples of K-type (C.A.-thermocouple) are installed circumferentially at an equal interval. Mixed mean temperature of air is also measured by K-type thermocouples at the locations shown in Fig. 2.

(2) Flow measurement

Flow rate of air in each subchannel is measured with an orifice plate.

(3) Data processing system

Data processing system is shown in Fig. 4. A data logger of HP-3497A and a mini-computer of HP-9845C are the main parts of the data processing system which connect an extender of HP-37203A.

4. Test conditions

Test conditions of No. 8 - 9 cycle operations are shown in Table 2 - 3.

3.2 Air-cooling channel

The hot gas ducts A and B were of single tube type with natural air-cooling. The cooling method of the half of hot gas duct A, however, was changed to forced air-cooling. Figure 2 shows the modified hot gas duct A with four subchannels which consists of a first elbow, a vertical tube, a second elbow and a horizontal tube. The cross-sectional view of air-cooling channel is shown in Fig. 3. The air-cooling subchannels surround the outside of pressure tube of hot gas duct. Each subchannel is isolated by separating plates. Flow rate of each subchannel is controlled individually by the control valve. Heat loss from hot gas duct to each subchannel is calculated from temperature rise and flow rate of cooling air. In order to prevent heat loss from air-cooling channel to the atmosphere, the air-cooling channel is covered with thermal insulation.

3.3 Measuring system

(1) Temperature measurement

Temperature of air is measured at mixing headers which are installed at the end of each subchannel. At the outlet of each mixing header, twenty thermocouples of K-type (C.A.-thermocouple) are installed circumferentially at an equal interval. Mixed mean temperature of air is also measured by K-type thermocouples at the locations shown in Fig. 2.

(2) Flow measurement

Flow rate of air in each subchannel is measured with an orifice plate.

(3) Data processing system

Data processing system is shown in Fig. 4. A data logger of HP-3497A and a mini-computer of HP-9845C are the main parts of the data processing system which connect an extender of HP-37203A.

4. Test conditions

Test conditions of No. 8 - 9 cycle operations are shown in Table 2 - 3.

5. Test results

5.1 Effective thermal conductivity of internal thermal insulation

A heat flux at the pressure tube of each subchannel is obtained from the difference of inlet and outlet temperatures and flow rate of air.

$$q(i) = (T_{air,out}(i) - T_{air,in}(i)).C_p.G(i)/A(i) \qquad (1)$$

$$\overline{q} = \sum_{i=1}^{4} q(i)/4 \qquad (2)$$

i : number of subchannel

Then the effective thermal conductivity of internal thermal insulation is calculated by the following equation:

$$\lambda_{eff} = \frac{\overline{q}.r_o.\ln(r_o/r_i)}{T_{wi} - T_{wo}} \qquad (3)$$

Figure 5 shows a relationship between effective thermal conductivity of internal insulation layer and flow rate of air, when He gas pressure and flow rate are 2.0 MPa and 0.5 kg/s respectively.

Effective thermal conductivity of internal thermal insulation itself essentially can not be affected by ambient air flow. However, the measured effective thermal conductivity in the case of 2 Nm^3/min was by about 25 % as low as those in the other cases.

The differences might be attributed to some errors in measuring low flow rate of air with a large orifice flow meter of 15 Nm^3/min in full scale and also to large variation in temperature of the pressure tube. Therefore these data were excluded.

As for the effective thermal conductivity of the vertical tube, it was slightly higher than that of air and temperature of He gas.

The effective thermal conductivity of internal thermal insulation measured in the present test is shown in Fig. 6 and the one measured in the previous tests. The average value of effective thermal conductivities for horizontal and vertical tubes in the previous tests agree well with those in the present tests.

However, the difference of effective thermal conductivities between the previous data of horizontal and vertical tubes is much larger than present data. In the previous tests, effective thermal conductivity of vertical tubes was by about 35 % as large as that of horizontal tubes. While, in the present tests, effective thermal conductivity of vertical tubes was only 2.5 % as large as that of horizontal tubes. The difference between the both results seems to be caused by the following reasons:

(1) In the previous tests, heat flux meters were placed at the ordinary part of the pressure tube, not at the internal structure parts (stud, separating plate, etc.). That is, the data obtained in the previous tests correspond to the thermal conductivity of internal insulation layer itself. On the other hand, the data obtained in the present tests are the average thermal conductivity of both ordinary and internal structure parts.

(2) In the present tests, thermal conductivities of horizontal and vertical tubes might be affected by the elbow.

However, it would be very difficult to conclude which result is more reliable, because the accuracy of both methods seems to be nearly the same. For instance, the standard deviation of the previous data is about 0.013 which is nearly the same as the present data.

The relationship between the effective thermal conductivity and He gas pressure is shown in Fig. 7. The effective thermal conductivities of both vertical and horizontal tubes are almost the same in a pressure range of 1.0 - 4.0 MPa.

5.2 Temperature of air

Average temperature of air at the inlet and outlet of each subchannel was calculated from the readings of five thermocouples. Figures 8 - 15 show temperature distributions of air in the flow direction. Temperature of air increased almost linearly in the flow direction and those of four subchannels were nearly the same.

5.3 Tempearture of the pressure tube

Temperatures of the pressure tube were measured at inlet, middle and outlet locations of each subchannel. Two thermocouples were fixed on the pressure tube at each location. The average temperture of two thermocouples was used as the temperature of pressure tube at each location.

Figures 16 - 23 show temperature distributions of the pressure tube in the flow direction. The temperature difference in the circumferential direction was found remarkable. As flow rate of air decreases, temperature variation ranges in both axial and circumferential directions become larger. The maximum differences in both directions are about 50°C and 30°C respectively when temperature of He gas is 950°C and flow rate of air 8.0 Nm^3/min. This might be due to the effect that flow distribution in the four subchannels was not uniform.

Similar results were reported in the test with a coaxial hot gas duct(4). In the case of coaxial hot gas duct, if flow distribution in an annular passage is not uniform, a large temperature difference will appear around the inner tube. A flow straightner might be necessary at an equal interval in the axial direction.

6. Conclusion

The following conclusions were derived.

(1) Effective thermal conductivity of internal thermal insulation obtained from temperature rise and flow rate of air was approximately constant when flow rate of air was 4 - 8 Nm^3/min.

(2) Effective thermal conductivity of the vertical tube was by 2.5 % as high as that of the horizontal tube. This difference was smaller than that of the previous data obtained with heat flux meters. However, average effective thermal conductivity of the vertical and horizontal tubes agreed well in both previous and present tests.

in the flow direction and those of four subchannels were nearly the same.

5.3 Tempearture of the pressure tube

Temperatures of the pressure tube were measured at inlet, middle and outlet locations of each subchannel. Two thermocouples were fixed on the pressure tube at each location. The average temperture of two thermocouples was used as the temperature of pressure tube at each location.

Figures 16 - 23 show temperature distributions of the pressure tube in the flow direction. The temperature difference in the circumferential direction was found remarkable. As flow rate of air decreases, temperature variation ranges in both axial and circumferential directions become larger. The maximum differences in both directions are about 50°C and 30°C respectively when temperature of He gas is 950°C and flow rate of air 8.0 Nm^3/min. This might be due to the effect that flow distribution in the four subchannels was not uniform.

Similar results were reported in the test with a coaxial hot gas duct(4). In the case of coaxial hot gas duct, if flow distribution in an annular passage is not uniform, a large temperature difference will appear around the inner tube. A flow straightner might be necessary at an equal interval in the axial direction.

6. Conclusion

The following conclusions were derived.

(1) Effective thermal conductivity of internal thermal insulation obtained from temperature rise and flow rate of air was approximately constant when flow rate of air was 4 - 8 Nm^3/min.

(2) Effective thermal conductivity of the vertical tube was by 2.5 % as high as that of the horizontal tube. This difference was smaller than that of the previous data obtained with heat flux meters. However, average effective thermal conductivity of the vertical and horizontal tubes agreed well in both previous and present tests.

(3) Temperature of air increased linearly in the flow direction.

(4) Temperature of the pressure tube varied much in both axial and circumferential directions. These temperature variations depend on flow patterns of air.

(5) In the case of coaxial hot gas duct, it is important to get uniform flow distribution in order to prevent hot spots at the surface of pressure tube.

Nomenclature

$A(i)$: Surface area of hot gas duct in each subchannel
C_p : Specific heat of air
$G(i)$: Flow rate of air in each subchannel
i : Number of subchannel
$q(i)$: Heat flux per unit area of pressure tube in each subchannel
$\bar{q}$: Average heat flux per unit area of pressure tube
r_i : Inner radius of internal insulation layer
r_o : Outer radius of internal insulation layer
$T_{air,in}(i)$: Inlet temperature of subchannel
$T_{air,out}(i)$: Outlet temperature of subchannel
T_{wi} : Average temperature of liner tube
T_{wo} : Average temperature of pressure tube
λ_{eff} : Effective thermal conductivity of internal insulation

References

(1) Japan Atomic Energy Research Institute : Status of R & D on VHTR in JAERI (1980-1983).

(2) Hishida, M et al. : Thermal Performance Test of the Hot Gas Ducts of HENDEL (in Japanese), JAERI-M 83-180 (1983).

(3) Kunitomi, K et al. : Temperature Distribution Measurement in the Hot Gas Duct of HENDEL (Results of Test No.1 Cycle and No.2 Cycle Operations) February, 1982 - October, 1982, (1983).

(4) Ohkuma, T et al. : Analysis of Coaxial High-Temperature Gas Duct by Beam Theory (in Japanese), JAERI-M 8775 (1980).

Table 1 Main items of the test apparatus

Flow rate of air in subduct	3 - 7.5 Nm³/min
Maximum temperature of air	150 °C
Blower	
Moter power	7.5 kW
Pressure head	600 mm aq
Orifice flow meter	
Maximum pressure drop	200 mm aq
Number of measuring locations	
Temperature of pressure tube	176
Temperature of air	100
Heat flux of pressure tube	12
Flow rate of air	4

Table 2 Test conditions of the hot gas duct (No.8 cycle operation)

Item / Test No.	Heater H_{32} Outlet temp.	Flowrate of He gas(kg/s)	Pressure of He gas(MPa)	Flowrate of air(Nm³/min)
1	500 °C	0.5	2.0	2.0
2	500	0.5	2.0	4.0
3	500	0.5	2.0	6.0
4	500	0.5	2.0	8.0
5	950	0.5	2.0	2.0
6	950	0.5	2.0	4.0
7	950	0.5	2.0	6.0
8	950	0.5	2.0	8.0

Table 3 Test conditions of the hot gas duct (No.9 cycle operation)

Item / Test No.	Heater H_{32} Outlet temp.	Flow rate of He gas (kg/s)	Pressure of He gas (MPa)	Flow rate of air (Nm^3/min)
1	450 °C	0.5	1.0	8.0
2	450	0.5	1.0	6.0
3	950	0.5	1.0	8.0
4	950	0.5	1.0	6.0
5	950	0.5	4.0	8.0
6	950	0.5	4.0	6.0
7	850	0.5	4.0	8.0
8	850	0.5	4.0	6.0
9	750	0.5	4.0	8.0
10	750	0.5	4.0	6.0
11	650	0.5	4.0	8.0
12	650	0.5	4.0	6.0
13	550	0.5	4.0	8.0
14	550	0.5	4.0	6.0

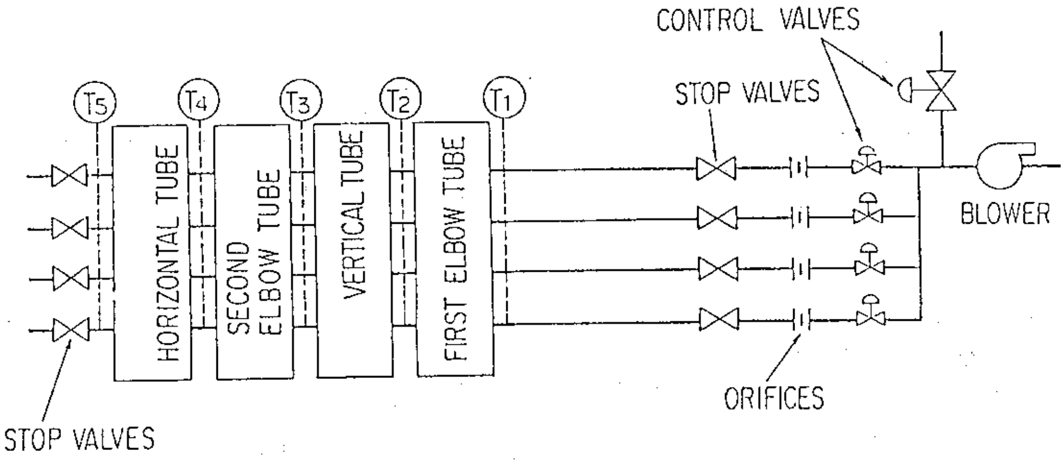

Fig. 1 Flow sheet of test apparatus

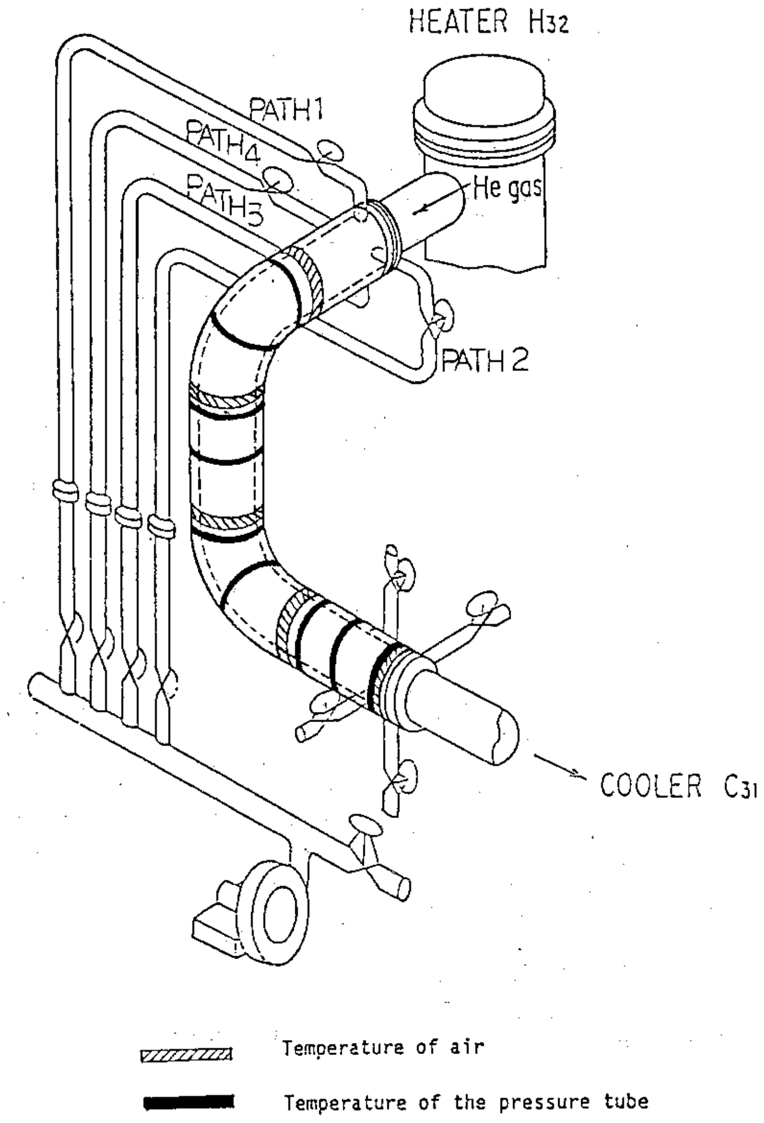

Fig. 2 Measuring locations of air-cooling channel

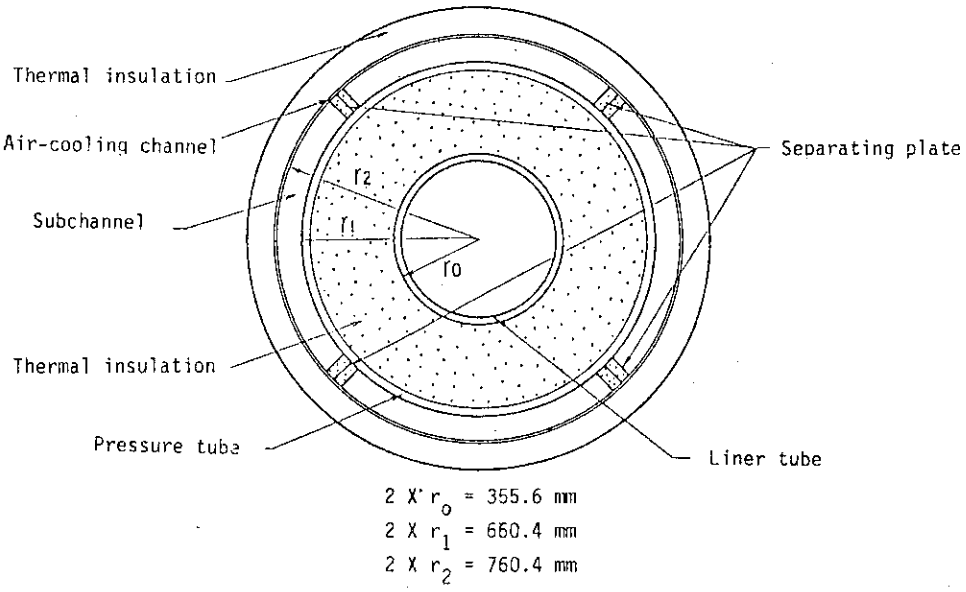

Fig. 3 Cross-sectional view of air-cooling channel

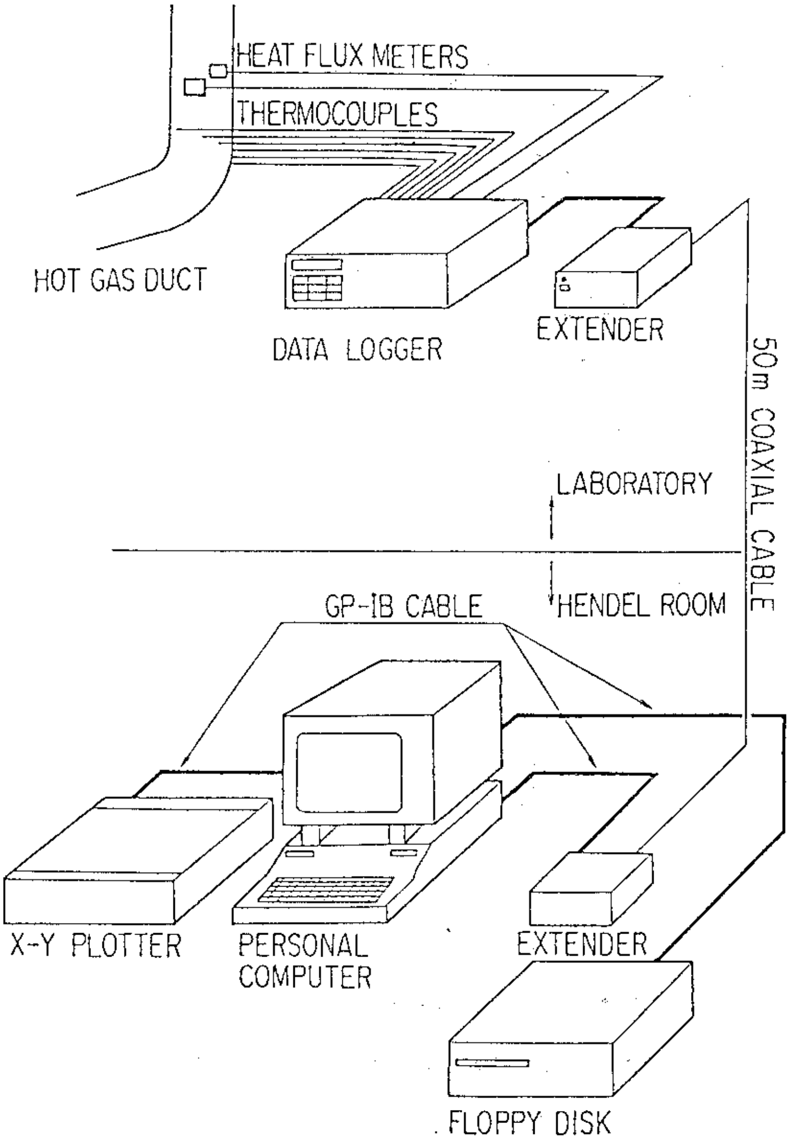

Fig. 4 Data processing system

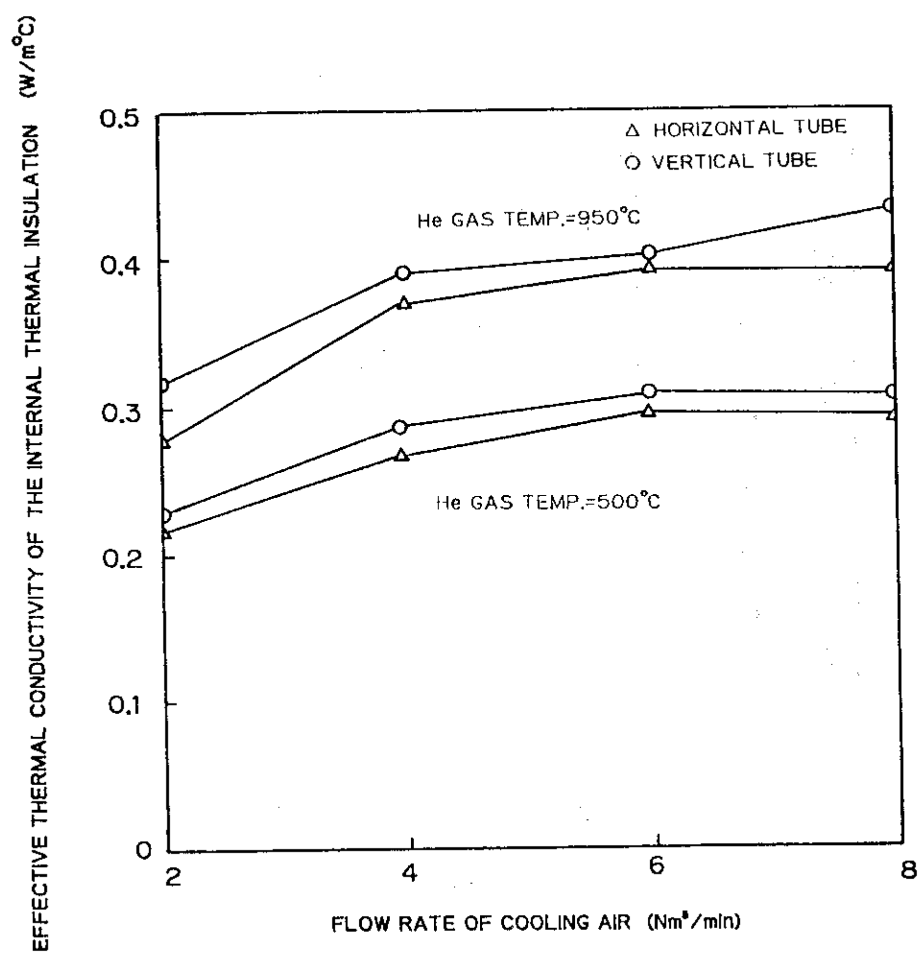

Fig. 5 Effective thermal conductivity of internal thermal insulation versus flow rate of air

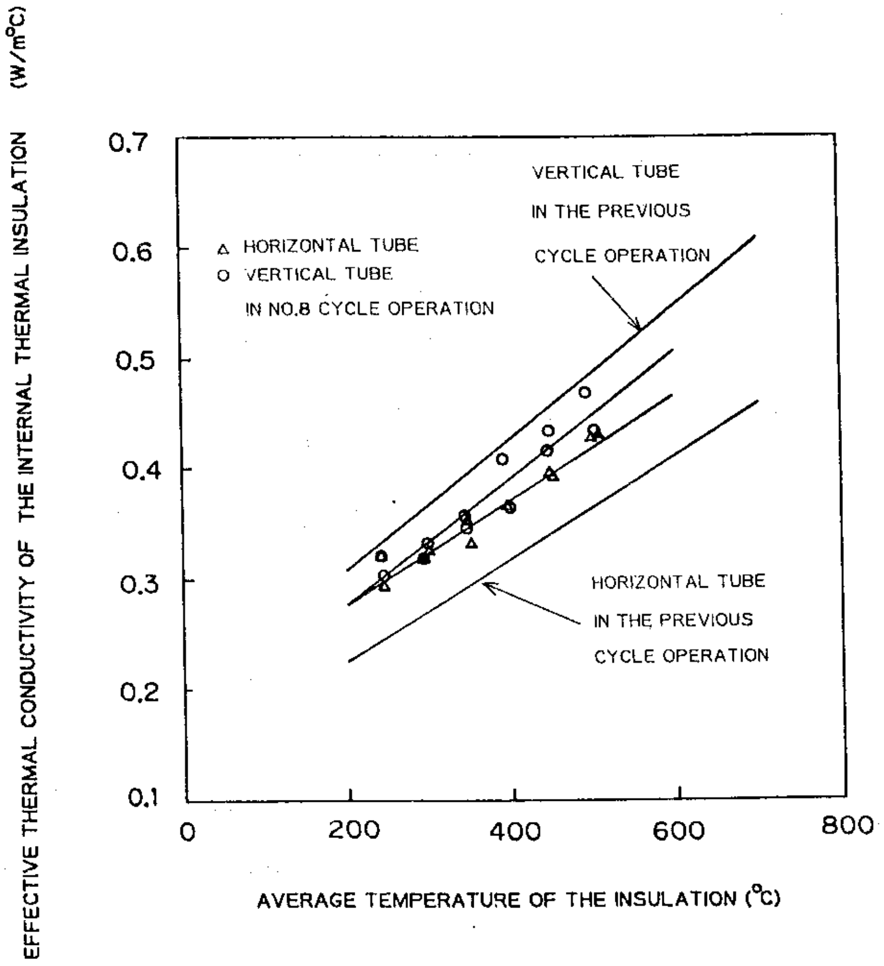

Fig. 6 Comparison of effective thermal conductivity obtained by heat flux meter and by air-cooling system

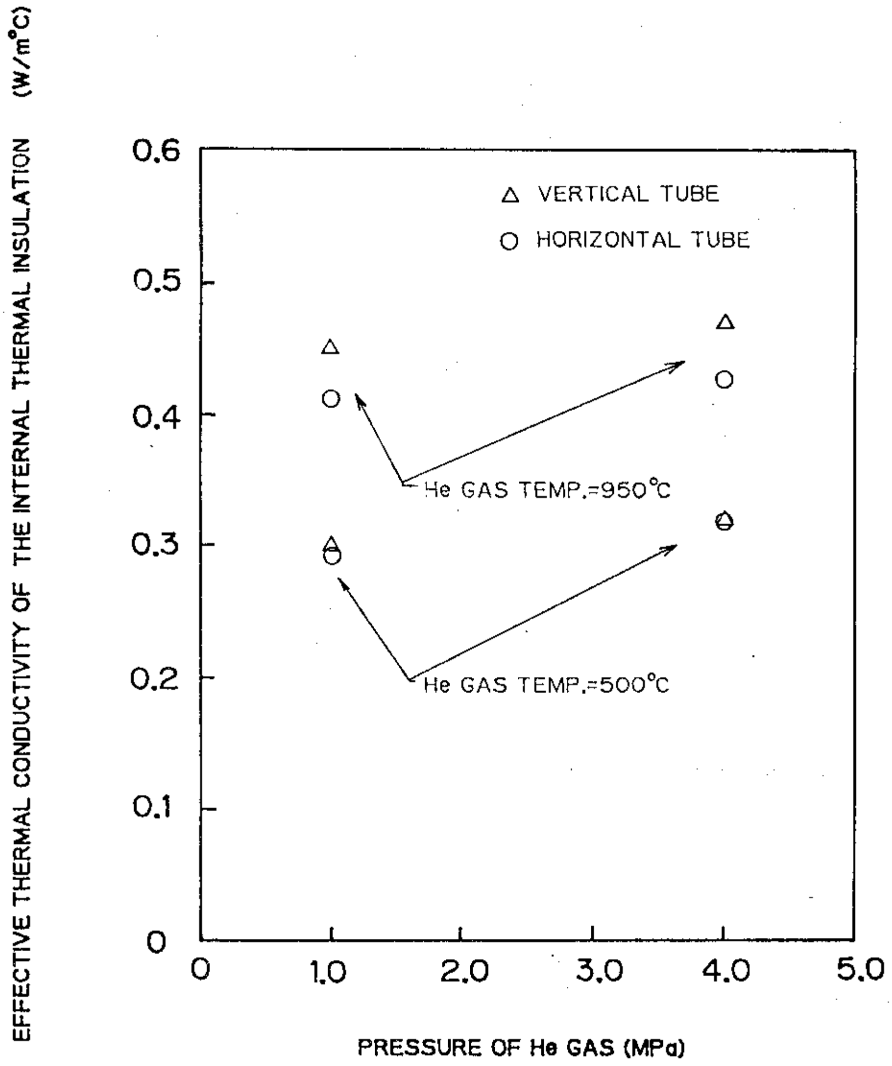

Fig. 7 Relationship between the effective thermal conductivity and pressure of He gas

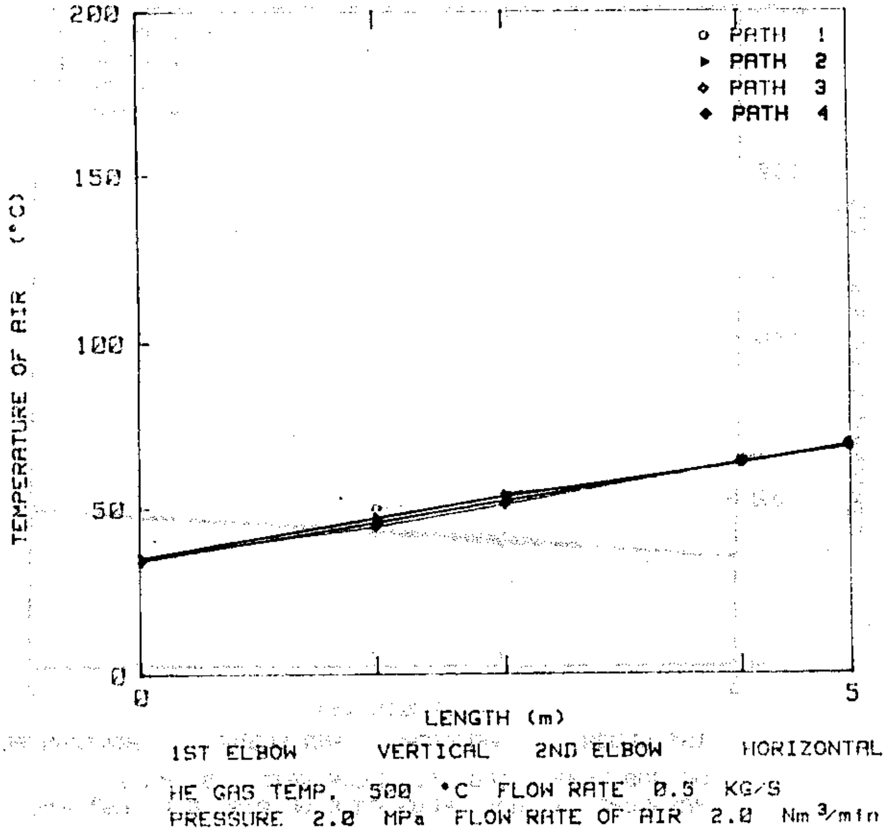

Fig. 8 Temperature distribution of air (1)

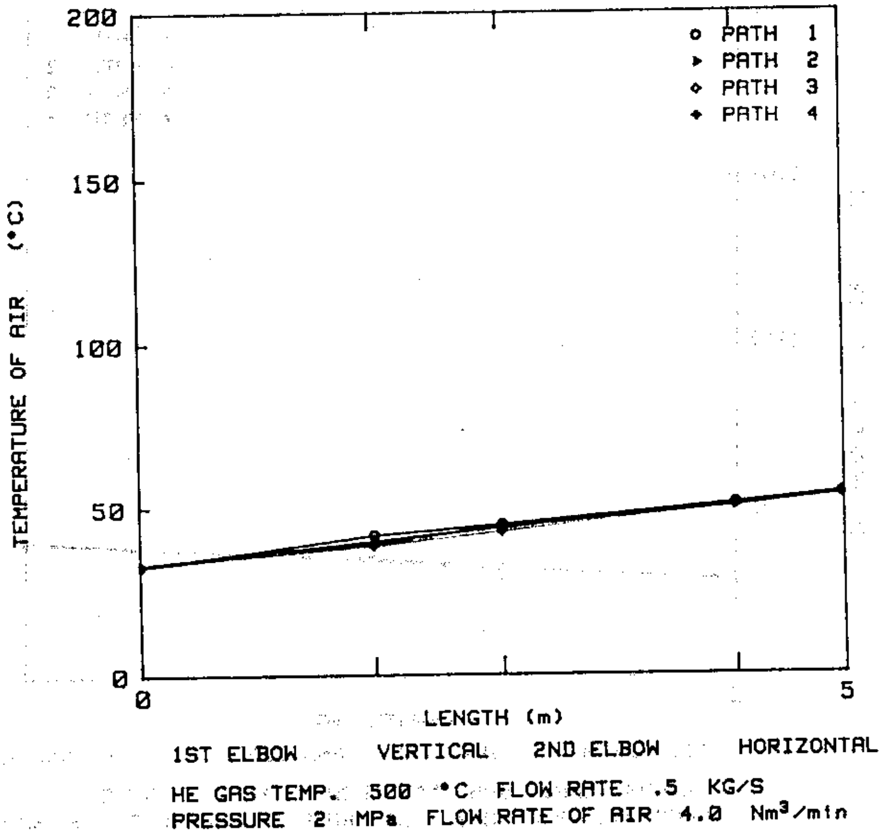

Fig. 9 Temperature distribution of air (2)

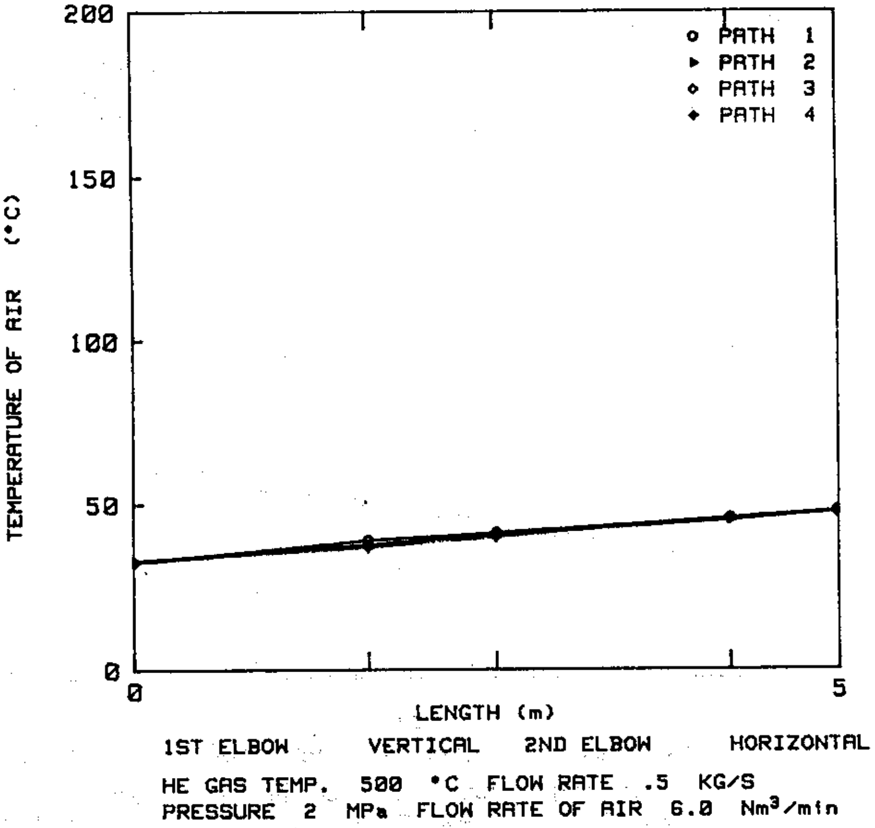

Fig. 10 Temperature distribution of air (3)

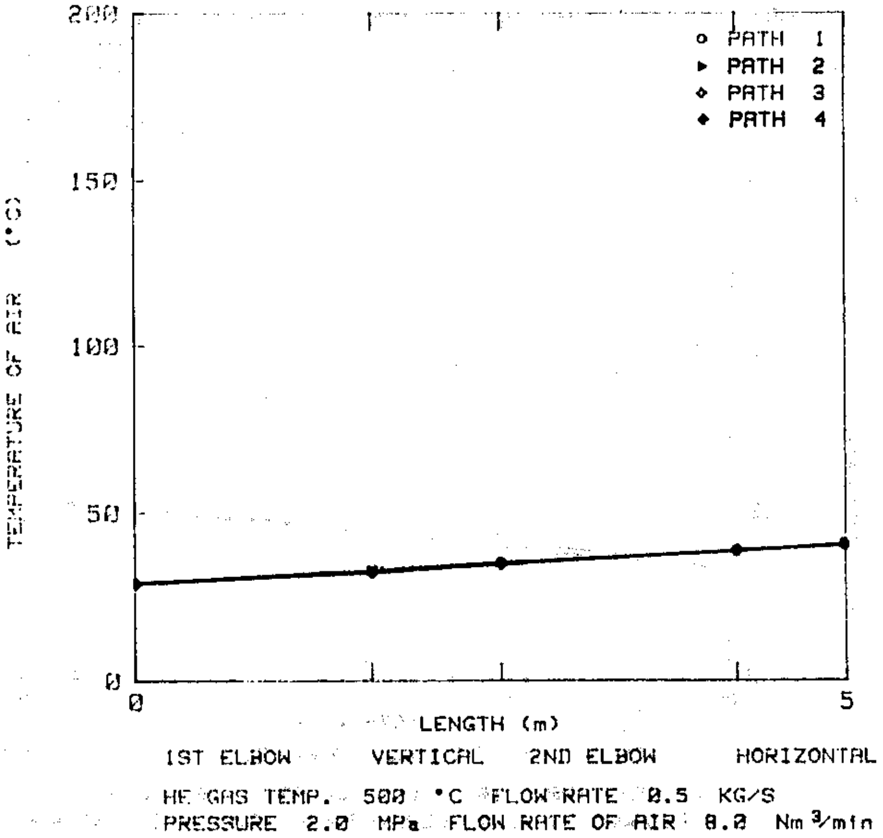

Fig. 11 Temperature distribution of air (4)

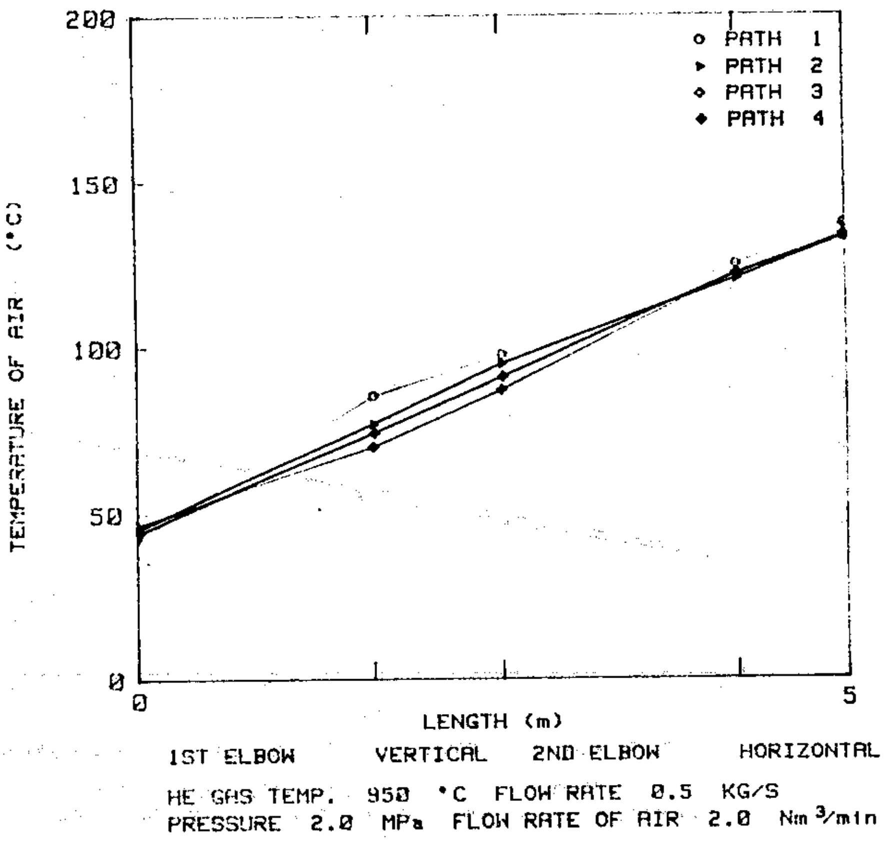

Fig. 12 Temperature distribution of air (5)

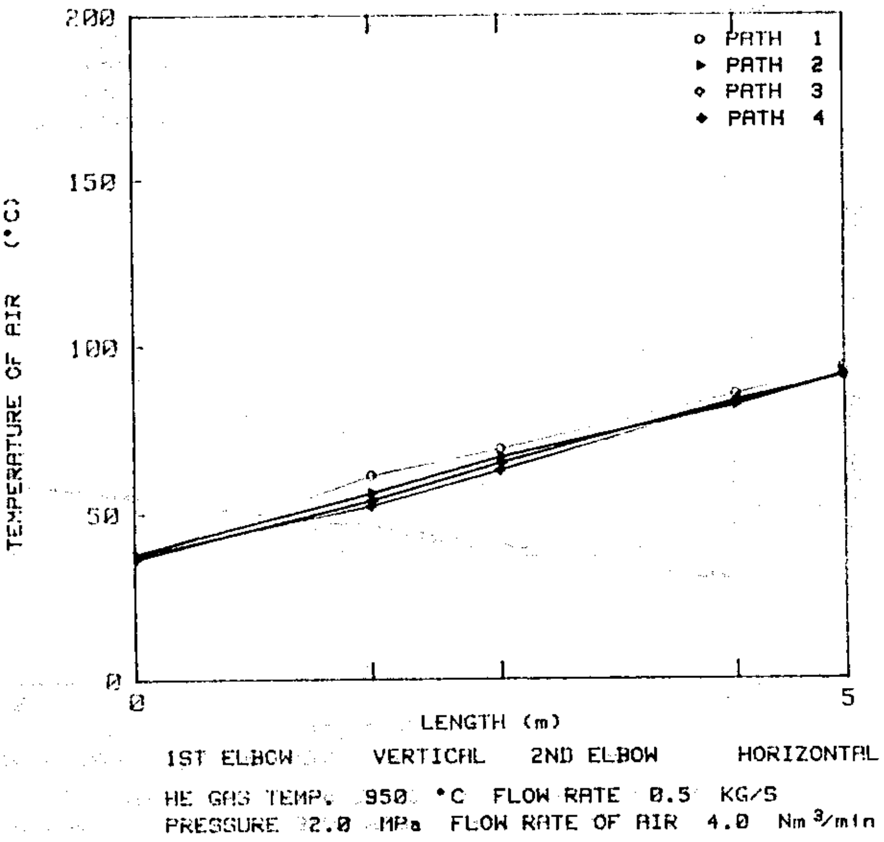

Fig. 13 Temperature distribution of air (6)

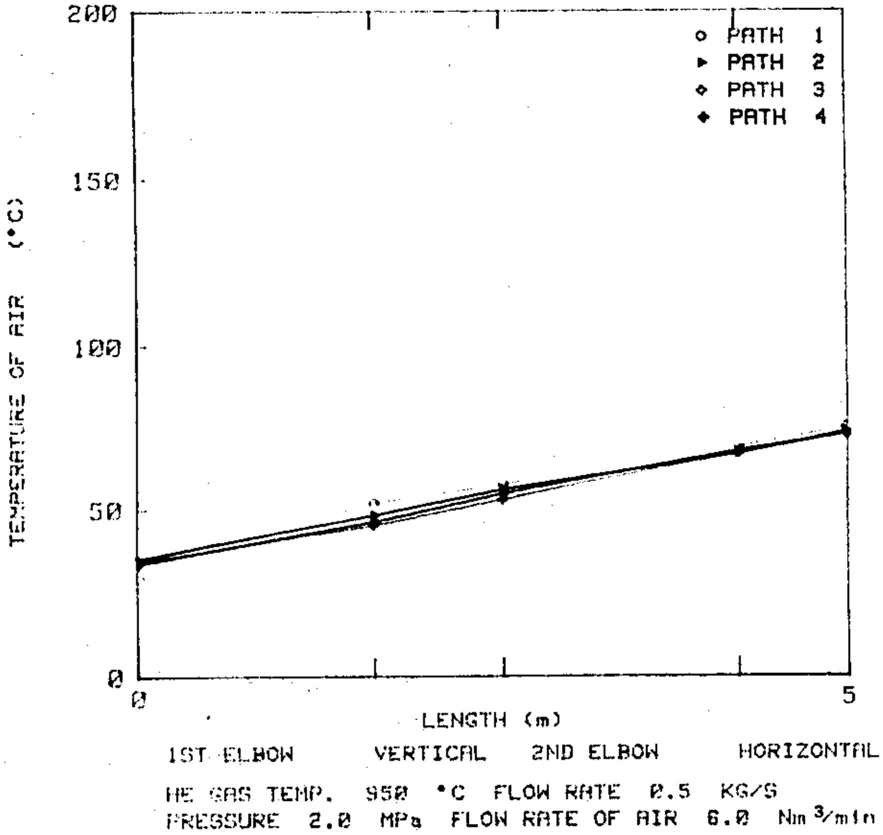

Fig. 14 Temperature distribution of air (7)

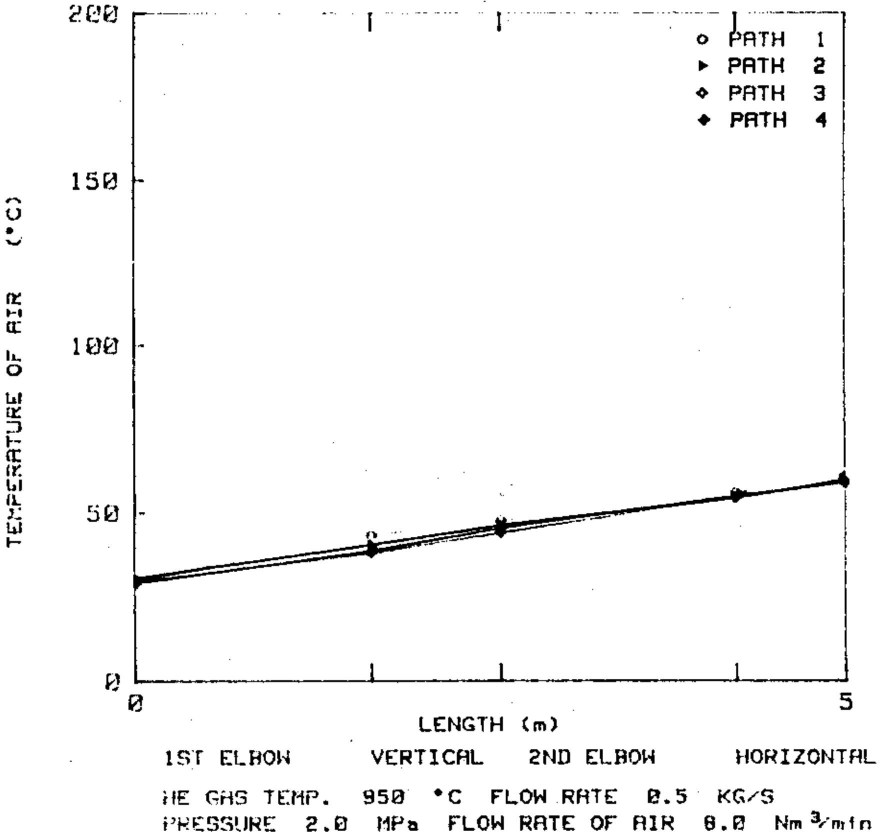

Fig. 15 Temperature distribution of air (8)

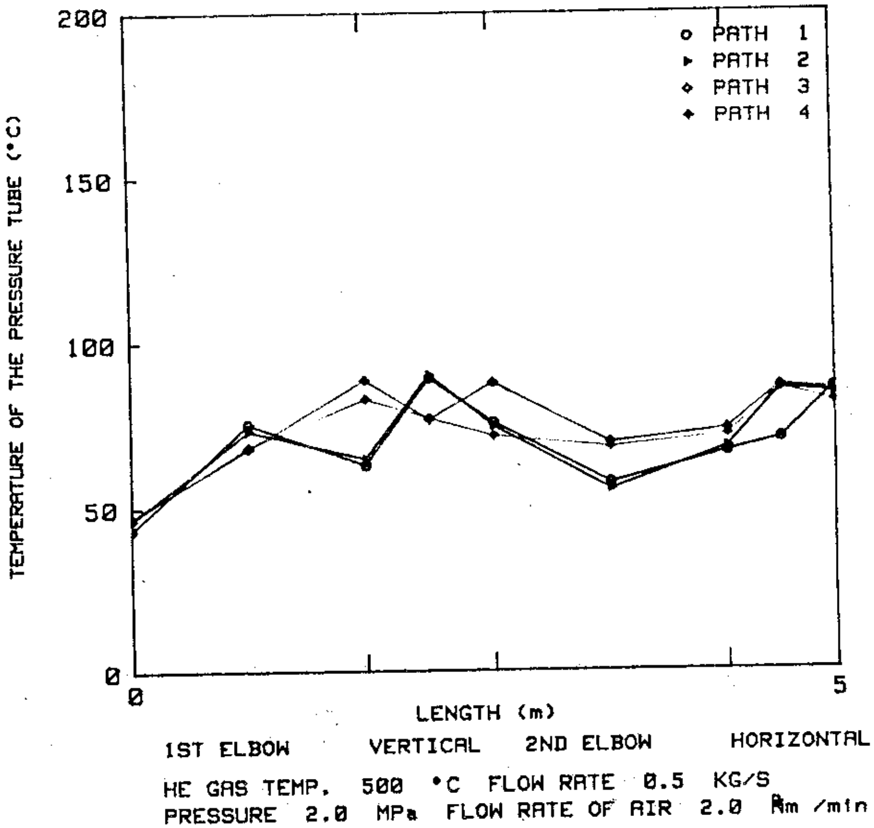

Fig. 16 Temperature distribution of the pressure tube (1)

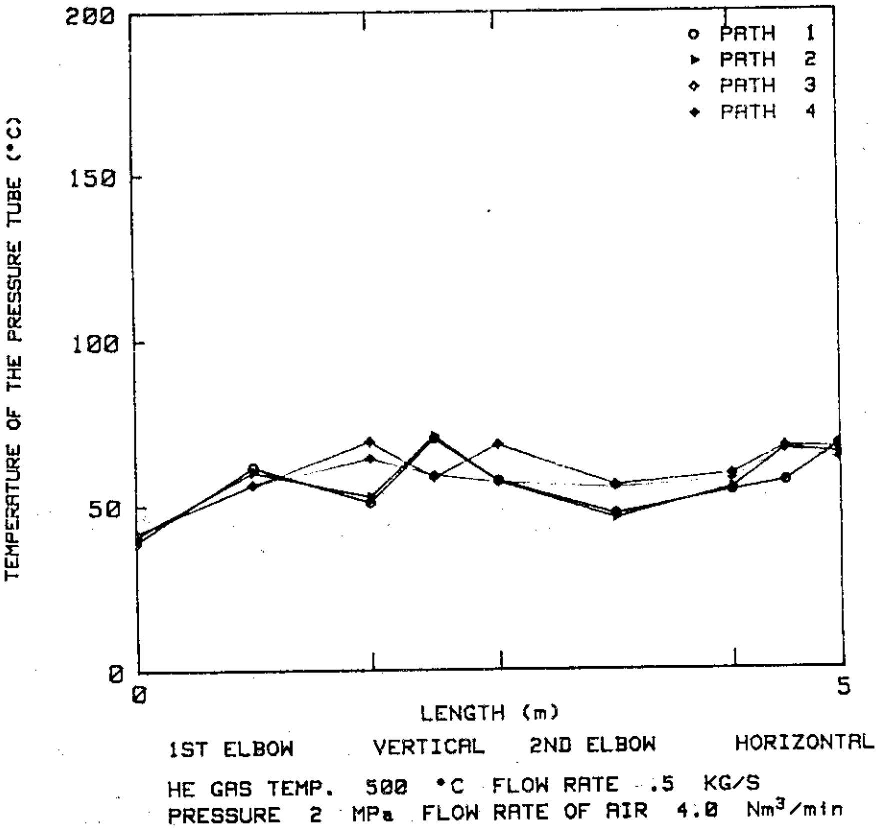

Fig. 17 Temperature distribution of the pressure tube (2)

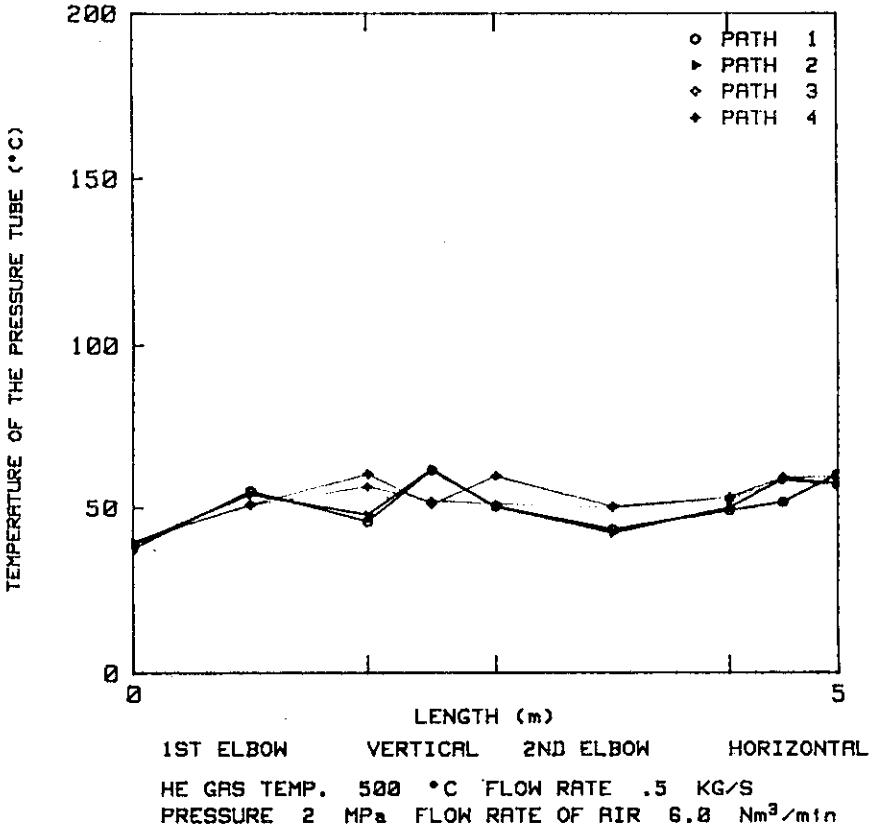

Fig. 18 Temperature distribution of the pressure tube (3)

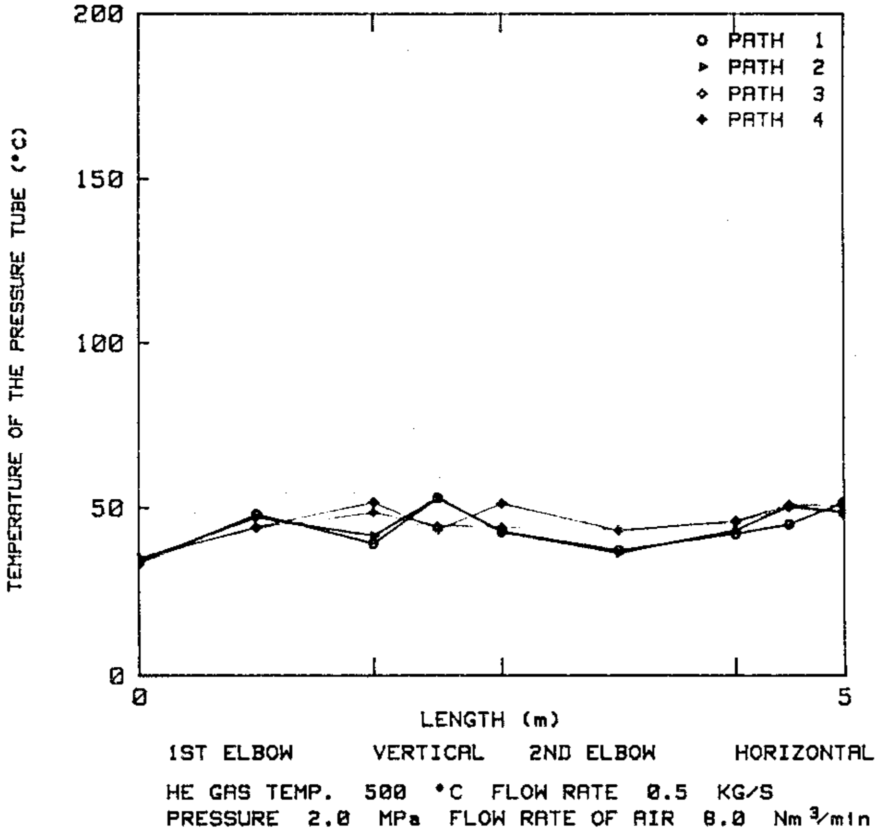

Fig. 19 Temperature distribution of the pressure tube (4)

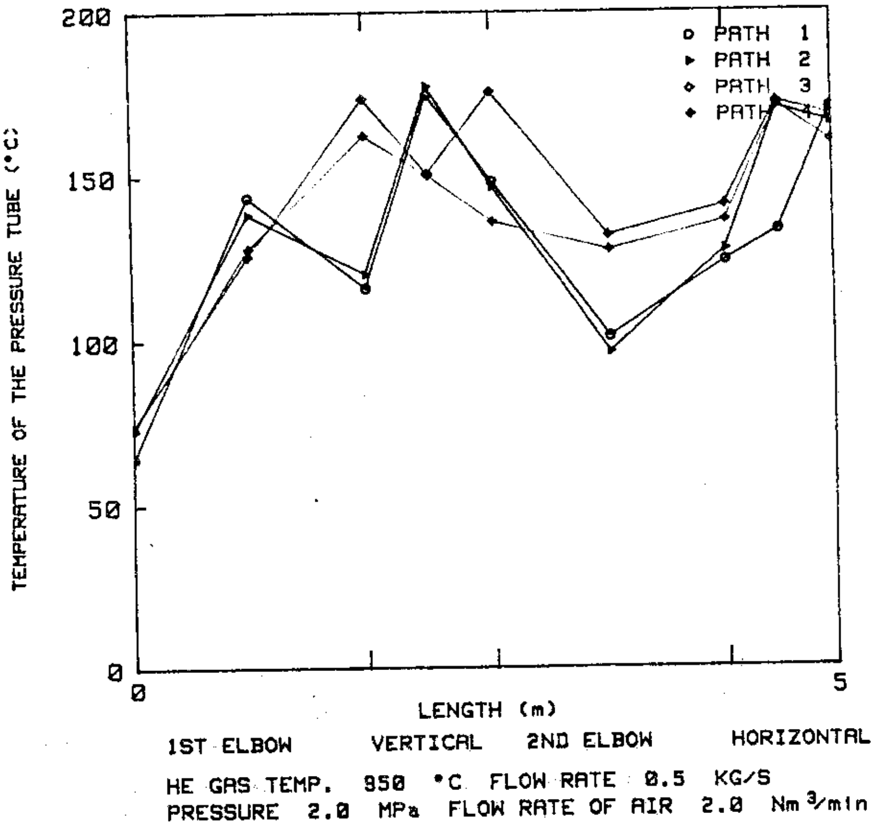

Fig. 20 Temperature distribution of the pressure tube (5)

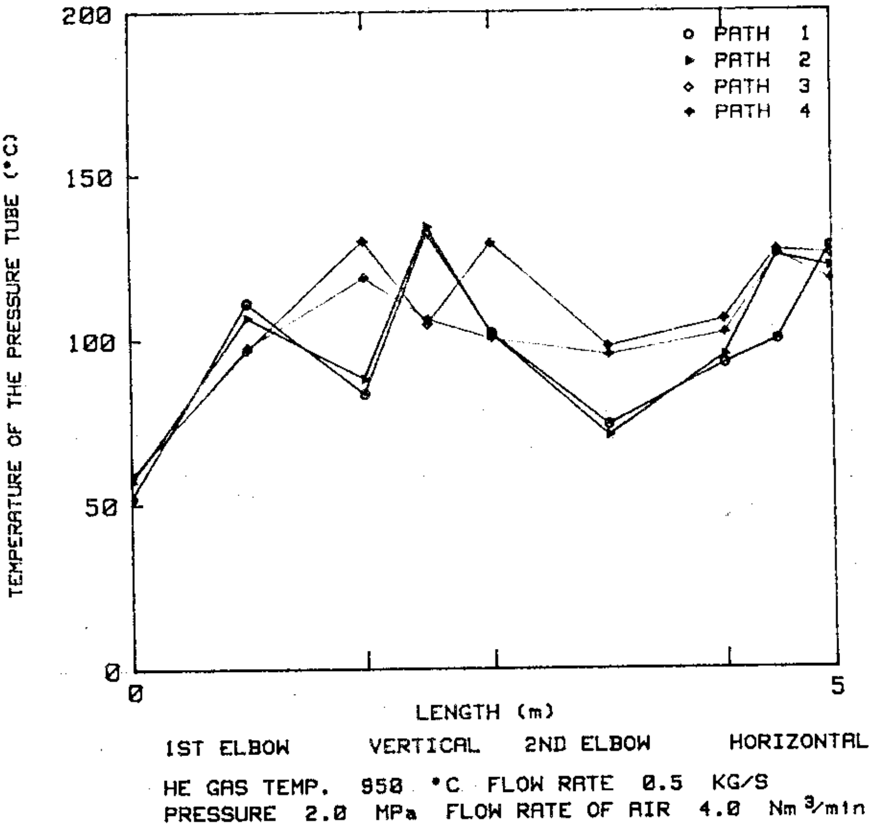

Fig. 21 Temperature distribution of the pressure tube (6)

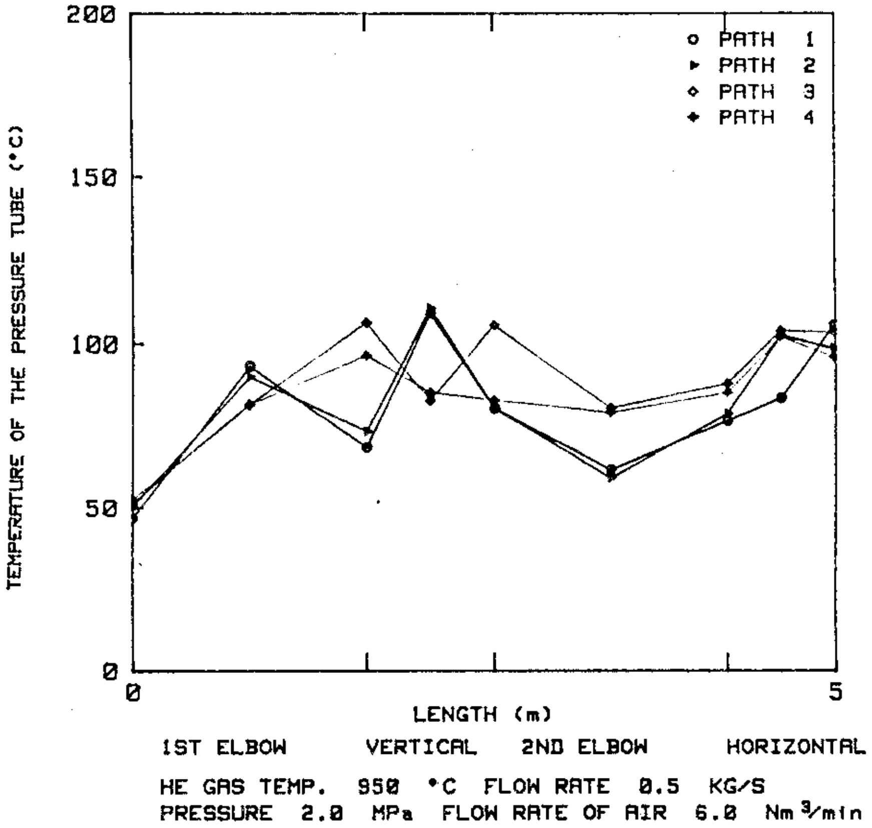

Fig. 22 Temperature distribution of the pressure tube (7)

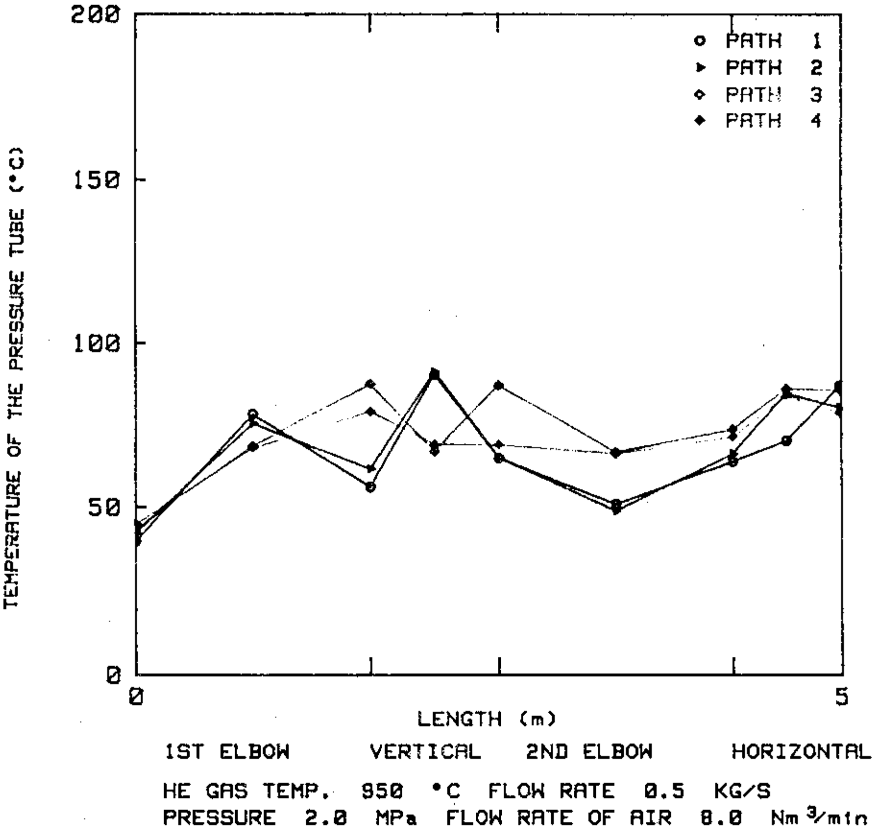

Fig. 23 Temperature distribution of the pressure tube (8)