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DATA PACKAGE FOR THE VALIDATION OF COMBUSTION SIMULATION CODES

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ABSTRACT

Many computer programs exist for predicting conditions inside a furnace during the combustion of solid and liquid fossil fuels. To verify that these prediction routines model reality correctly, it is necessary that measurements be taken in a combustor which is easily modelled and resembles a full-scale combustor. This paper discusses the generation and use of a data package for the validation of a computer model of a horizontally fired, cylindrical, research tunnel furnace.

The eleven experiments discussed in this paper involved the combustion of either coal or oil. The volatile content of the coal varied from 21 to 35 % by weight and the swirl number of the flow varied from 0.0 to 0.4. The measurement scheme included the axial variation of the total and radiant heat flux from the flame and mapping of the gas temperature and major species concentration profiles. To complete the measurements inside the furnace, a mapping of the gas velocity profiles was made at two total airflow rates and seven swirl settings ranging from a swirl number of 0.0 to 0.9.

This study used a computer code called 'MODTUN' which was developed at the Imperial College. This computer program is based on the 'TEACH' code and incorporates the necessary sub-routines to model the devolatilization and combustion of pulverized coal. A reasonable measure of success was obtained when the measured data were compared with the predicted data. By using this data package not only was it possible to determine the appropriate models for the physical processes involved but empirical parameters for these models were also identified. The most significant of these is the amount of volatile material released relative to that predicted by proximate analysis.

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INTRODUCTION

There are two ways to study the conditions inside combustion devices. The first is to mount an experimental campaign to measure the quantities. If the information required is of a limited quantity and of a general nature then the experimental method is generally preferred. However, as the amount of information required and the number of independent variables increase, so too will the cost of the experimental enquiry. The second is to model the processes which occur inside the combustion device by means of a computer program. The level of sophistication of the computation routines can vary from calculating the global input-output relationship for a combustion process to determining the temperature and concentration fields in the combustor itself. The computer modelling techniques are less time consuming and less costly in the long run when compared to the experimental methods. As a result the test matrix used in modelling programs can be much larger than that used in experimental programs. For this reason, the computer modelling techniques are used in parametric studies where the number of parameters studied is much larger than that permitted with experimental techniques. Furthermore, the responses of the particles in a combusting environment to the near burner aerodynamics of a full-scale furnace cannot be well simulated by a smaller scale facility. This fact must be kept in mind when interpreting smaller scale data pertinent, for example, to flame stability and NO_x prediction. Extrapolation of near-burner phenomena to the large-scale is best facilitated by a reliable mathematical model. The one drawback with modelling techniques is that the output of the program is only as good as the computer program itself.

The various simulation programs in the literature are made up of several sub-models which describe the individual physical processes occurring inside the combustion field. As the understanding of these processes improves, so too does the accuracy of the output of the programs. Experimentation has proven useful in gaining a better understanding of these processes. As a result, a symbiotic relationship has developed between the computer modelling and experimental investigative techniques. The experimental methods have provided the empirical parameters for the sub-models and a means for the validation of the computer programs. The computer programs have, in return, provided an insight into the processes

which occur in the combustion field. Both techniques have been used in a hybrid experimental/computer model test series. The test series has been less costly and less time consuming than if experimentation alone were used.

These computer programs are continuously undergoing refinements due to improvements in the understanding of the sub-models and the empirical parameters used. To validate these improvements, these models must give a true representation of the processes occurring in real combustion devices. Since these programs are used to make predictions in large industrial size furnaces, the validation experiments must be carried out in a large-scale combustor. The research tunnel furnace facility at CANMET has been used to generate reference data for comparison with computer simulation programs (1,2,3). The furnace is easy to model with the minimum of assumptions due to its cylindrical geometry. Furthermore, the tunnel furnace is sufficiently large to ensure fully turbulent flow and as such the scale-up characteristics are well understood. Thermal radiation is one of the significant heat transfer mechanisms in a full scale furnace. Coal flames are known to be characterized by large absorption coefficients. Thermal radiation is significant for path lengths as small as 0.5 m in these types of flames. The CANMET furnace has a diameter of 1.0 m and because of this the thermal radiation transfer to its walls is substantial. The CANMET tunnel furnace facility is therefore able to simulate the heat transfer mechanisms in large scale devices.

Compared with the enormous variability of coal, the amount of available combustion data for model validation purposes is very limited. Apart from the efforts undertaken by CANMET, the institutions active in data collection are limited to the International Flame Research Foundation, Brigham Young University (5), and Imperial College (6). It is felt that the CANMET data, reported herein, constitute an important addition to the sparse databank already available. This is true particularly for the low-volatile coals which are assuming an increasingly more important role among industrial users.

THE CANMET TUNNEL FURNACE

The furnace is shown in Fig. 1 and Fig. 2 shows a schematic of its interior. The combustion chamber is approximately 5.0 m long and 1.0 m in diameter. For these experiments, the initial 0.75 m of the furnace was lined with refractory to allow for radiative exchange to the fuel on entering the furnace and enhance the devolatilization of the fuel. The remaining 4.25 m of the furnace is surrounded with a cooled wall to simulate a thermal load on the gases in the furnace. The cooled portion of the furnace is divided axially into 28 individually cooled sections each in the form of a 'C' (Fig. 1). Each 'C' section is monitored for temperature rise and flowrate and thus acts as a calorimeter. The open portion of all the 'C' sections when put together forms an axial slot along the length of the furnace. This slot allows for the insertion of probes for measuring in the gases in the furnace.

The furnace is designed to burn both solid and liquid fuels with a maximum firing rate of about 0.6 MW. Any burner configuration could be used on this furnace; however, the burner used in these studies has a moving block type of swirl generator, similar to that used elsewhere (7). A schematic of the interior of the furnace, including the entrance region, is shown in Fig. 2. As the swirl is adjusted, the flow of air in the swirled annulus is not obstructed. Only the magnitude of the tangential component is changed. Thus only the swirl number is changed and the primary to secondary air ratio is maintained constant. The primary air and pulverized coal are carried to the furnace through the central 9.53 cm pipe. For these tests, the primary air was not given a swirl component. Various bluff bodies were used for some of the combustion experiments to improve the combustion of the low-volatile coals. The entrance region of the furnace showing the geometry of the bluff bodies is shown in Fig. 3a and 3b.

DESCRIPTION OF EXPERIMENTS

The data package produced by these experiments was intended to provide the modeller with the necessary information to validate the results of computer simulation codes for combusting environments. Most of these codes can be divided into subroutines dealing with the conditions inside the

furnace without combustion and those including combustion. The subroutines without combustion generally describe the flow of the gases and particulates through the furnace and involve turbulence and two-phase flow models. The combustion subroutines contain models which simulate the effect of the evolution of heat and volatiles resulting from the pyrolysis and combustion of the fuel. The experimental campaign was, therefore, designed to measure the necessary input information for the computation routines and a complete set of reference data for comparison with the program output for both the combusting and non-combusting cases.

Normally the conditions of the material entering the calculation domain and the boundary conditions of the furnace are all that is required to perform a computer analysis of a combustion device. For example, the input data for the non-combusting case would consist of the entrance velocity profiles and the interior geometry of the furnace; while for the simulation of combusting flow, the fuel flowrate and properties and the heat transfer boundary conditions at the furnace walls would also be included. The output of these computer programs is a map of the various fields within the gases, and the heat transfer characteristics between the gases and the furnace walls.

In order to generate data for the verification of the non-combusting flow subroutines, room temperature air was caused to flow through the swirl generator and then through the furnace. A five-hole pitot probe was used to measure the velocity vector profiles at various axial locations. These experiments were run at two total air flowrates (0.169 and 0.761 kg/s) and for seven swirl number settings from 0.0 to 0.9. The flowrates were chosen to simulate the range of gas velocities found in the tunnel furnace during combustion.

The experiments for the validation of the subroutines used for the simulation of combustion involved the combustion of various fuels (light oil, low- and high-volatile coal) in the tunnel furnace at various swirl numbers. The measurements consisted of gas temperature and composition profiles and wall and radiant heat fluxes at several axial locations. The volatility of the coals varied from 21.3 to 34.6% and the swirl number of the entrance flow ranged from 0.0 to 0.4.

In both the velocity profile and the combustion experiments every attempt was made to ensure consistency from one experiment to another. The furnace was allowed to equilibrate before any measurements were taken. For the velocity profile experiments, this required that the air flowrate and temperature stabilize in the primary and secondary air supply systems. For the combustion experiments, since measurements involving heat transfer and gas composition were to be made, two additional equilibrium parameters were monitored. The temperature at two depths in the adiabatic wall and the nominal excess oxygen at the furnace exit were used to determine the end of the transient development of conditions inside the furnace.

VELOCITY PROFILE MEASUREMENTS

A five-hole pitot probe was used to measure the velocity vector of the gases flowing through the furnace at various axial and radial positions. These measurements were made at the exit of the swirl generator ($x = 0.0$ m), at the quarl exit ($x = 0.38$ m) and at three axial locations in the tunnel portion of the furnace ($x = 0.79$, 1.07 and 1.37 m) (Fig. 2). A typical velocity profile is shown in Fig. 4 where the three rectangular velocity components are non-dimensionalized and plotted against radial position. The reference velocity used to non-dimensionalize the velocity components is an average axial velocity at the test section. The recirculation zones at the various swirl settings were mapped using the tuft technique.

The velocity profile measurements can be used to serve two purposes. The first is to validate the turbulent flow routines in the simulation program and thus a complete mapping of the furnace is required. The second is to provide the velocity profiles of the gases flowing into the computation domain for the combustion simulation. In the latter, only the velocity profile measurements at the exit of the swirl generator are necessary for each set of running conditions of the combustion experiments. To provide the optimum utility of the velocity measurements, two flow conditions for each of the swirl settings were chosen. This was done because it was impractical to use the exact running conditions of each of the combustion trials for the velocity measurements. At these two flow conditions it was verified that the burner operated in a similar manner at a

particular swirl setting regardless of the volume of air flow. This similarity of velocity profiles is shown in Fig. 5 to 7, where the non-dimensionalized velocity components are plotted against radial position for the two air flowrates. These figures are typical for the different swirl settings.

Thus the velocity profiles of the gases leaving the swirl generator for each of the combustion experiments can be inferred from the cold flow velocity profile measurements using continuity relations. The following equation is a general expression for the velocity of the gases leaving the swirl generator for the combustion experiments without the bluff bodies:

$$(V_{ij})_E = (m_j)_E/(m_j)_V \times [(\rho_j)_V/(\rho_j)_E] \times (V_{ij})_V \qquad (1)$$

where:

V = velocity

m = mass flowrate of air

ρ = air density

subscripts:

E = combustion experiments

V = velocity profile experiments

i = axial, radial or tangential components of the velocity

j = primary or secondary air portions of the profile

These velocity profile measurements can also be used to calculate the entrance velocity profiles for the combustion experiments with the two bluff bodies in the swirl generator. Two separate and independent air systems were used to supply the primary and secondary airflows. Therefore, the partial blocking of the primary flow caused by the bluff bodies does not cause a subsequent rise in the secondary flow. Thus a two step calculation scheme was determined to compute the gas velocity profiles for the combustion experiments from those measured. The effect of the different air flowrates between the combustion and the velocity profile experiments is decoupled from the effect of the deflection of the primary flow into the secondary flow.

Considering the experiments using the long bluff body (Fig. 3a), all of the velocity components in the primary airflow region are zero due to the presence of the bluff body. Thus, the air flow in the annular region will include the effects of the different flow conditions, i.e., air temperatures and flowrates, and of the deflection of the primary flow. These two effects were handled separately and the resultant expressions for the three components of velocity in the secondary airflow region are as follows:

$$(w_s)_E = (m_s)_E/(m_s)_V \times [(\rho_s)_V/(\rho_s)_E] \times (w_s)_V \quad (2)$$

$$(v_s)_E = [(m_p)_E \times \cos(60)]/[(\rho_p)_E \times (A_p)_E]$$

$$+[(m_s)_E \times (\rho_s)_V]/[(m_s)_V \times (\rho_s)_E] \times (v_s)_V \quad (3)$$

$$(u_s)_E = [(m_p)_E \times \sin(60)]/[(\rho_p)_E \times (A_p)_E]$$

$$+[(m_s)_E \times (\rho_s)_V]/[(m_s)_V \times (\rho_s)_E] \times (u_s)_V \quad (4)$$

where:

w = tangential velocity component

v = radial velocity component

u = axial velocity component

$(A_p)_E$= 31.104 cm

subscripts:

s = secondary flow region

For the short bluff body (Fig. 3b) only part of the primary air flow area is blocked by the bluff body. Therefore, equation (1) is used to determine the velocity components of the air flowing through the secondary air portion of the flow. In the primary air flow region all the velocity components are zero where the bluff body is located. In the gap between the edge of the bluff body and the primary air pipe, the u and v velocity components are determined from the following equation:

$$(u_p)_E = [(m_p)_E/(m_p)_V] \times \{[(\rho_p)_V \times (A_p)_V)/[(\rho_p)_E \times (A_p)_E]\} \times (u_p)_V \times \sin(60) \quad (5)$$

$$(v_p)_E = [(m_p)_E/(m_p)_V] \times \{[(\rho_p)_V \times (A_p)_V)/[(\rho_p)_E \times (A_p)_E]\} \times (v_p)_V \times \cos(60) \quad (6)$$

where:

$(A_p)_V$ = 71.331 cm

$(A_p)_E$ = 41.412 cm

subscript:

p = primary flow region

Figures 8 to 10 show a comparison between the measured axial velocity component and that calculated for three of the combustion experiments.

COMBUSTION EXPERIMENTS

The conditions for the combustion experiments and the fuels used are given in Table 1. The measurements for each of the combustion tests are listed in Table 2 along with the sample locations.

Each of the combustion tests were conducted in the same manner. The furnace was preheated for 2 h with a number two oil. As stated earlier, the refractory temperatures (in the quarl of the furnace) were used to determine that the furnace had attained a state of thermal equilibrium. At this time, the feed fuel was changed over to the investigation fuel. When the refractory temperatures and excess oxygen at the furnace exit had stabilized (after about 2 h), a complete series of measurements was taken in the furnace. The furnace was maintained under a slight positive pressure to ensure that ambient air did not contaminate the temperature and composition measurements. A sample plot of the total and radiated heat flux measured in one of the low-volatile coal combustion experiments is shown in Fig. 11.

Table 1 - Run conditions and fuels

Combustion Trial	Burner Geometry	Fuel Volatility (Wt %)	Swirl Number	Excess Oxygen (%)
A	Fig. 2	Oil, n.a.	0.000	5.0
B	Fig. 2	Oil, n.a.	0.184	5.0
C	Fig. 2	Coal, 34.59	0.000	5.0
D	Fig. 2	Coal, 34.59	0.086	5.0
E	Fig. 2	Coal, 34.59	0.025	5.0
F	Fig. 3a	Coal, 21.32	0.383	8.0
G	Fig. 3a	Coal, 21.32	0.334	8.0
H	Fig. 3b	Coal, 34.59	0.360	8.0
I	Fig. 3b	Coal, 34.59	0.354	8.0
J	Fig. 3b	Coal, 24.18	0.117	3.0
K	Fig. 3b	Coal, 24.18	0.372	3.0

Table 2 - Combustion test measurements and sample locations

Measurement	Probe or technique used	Location of measurement
Radial heat transfer	Temp. Rise in 28 'C' Circuits	After refractory at 28 axial locations on 15 cm centres
Radiative heat transfer	2 PI radiometer	Various axial locations including refractory zone
Gas concentration	Cooled probe continuous analyzers	Various axial and radial locations after refractory zone
Gas temperature	Water cooled suction pyrometer	Various axial and radial locations after refractory zone

MEASUREMENT ERRORS

Attempts were made to minimize the measurement errors in all of the experiments. The errors involved with the velocity profile experiments are expected to be from 5 to 8%. This is covered in greater detail elsewhere (8). The greatest uncertainty in the computation of the entrance velocity profiles is suspected to be found for the combustion experiments using the short bluff body (Fig. 3b). The uncertainties in the computation of any of the entrance velocity profiles are expected to be small and will have only a minor effect on the predictive accuracy of the computer programs as a whole. The uncertainties involved with the combustion and heat transfer modelling are expected to play a much more prominent role in the accuracy of the simulation of the conditions inside the furance. The standard procedure in combustion simulation validation is to invoke continuity and assume flat entrance velocity profiles. The shaping of the velocity profiles based on cold flow measurements, as done in this paper, is expected to effect prediction uncertainties at a level well below errors arising from other assumptions.

The errors involved in the combustion measurements are expected to be from 2 to 5% with one exception. Non-isokinetic techniques were used to extract the gases from the furnace for the species concentration profiles. The resulting errors are not readily determined, but are not expected to exceed 10 to 20% (9).

LIMITATIONS OF CANMET DATA

No data set is ever complete and this is especially true of coal furnace experiments where the difficulties of measurement are extreme. Previous work in pulverized coal firing computer validation suggests that existing computer models work relatively well (1,10). Yet on closer examination, it is clear that the available data, including those presented here, are for measurement stations which are relatively far downstream. Now, much of the current industrial interest concerns the so-called 'near burner field'. The aerodynamics and combustion in the immediate vicinity of the burner govern the important phenomena of flame stability and NO_x generation. Accurate measurements in this region of a pulverized fuel (PF)

flame are extremely difficult, due to the disturbance of the velocity and temperature fields caused by the presence of the probes in the flame. Furthermore the harsh environment can result in the blockage of and damage to the probes.

The second most obvious omission from PF data sets are measurements of velocity in the flame. Laser-doppler anemonetry has been much vaunted for this purpose but successes to date are nonexistent. In principle, the velocities of both the particulate and gaseous phases can, with suitable LDA development, be measured non-intrusively. Some of the major problems facing the developers of this instrumentation are:

- beam blockage due to the high particulate concentrations in the near burner region
- problems associated with phase discrimination over the size range of typical PF flames
- refraction of the beams due to density fluctuations over the large dimensions of the furnace.

The separate measurement of the local gas and particle temperatures, as opposed to a mixed mean of the two which is obtained by conventional probes, would be highly desirable; however, this is impractical in any combustor of engineering dimensions and conditions. The CANMET data do not contain this information, nor indeed do any other data sets.

Char burn-out data can be determined with good precision and has emerged as being of considerable use to the modeller. Nonetheless, it is usual for only scattered burnout data to be collected during furnace trials and this is the case for the present data set. Although it is rarely reported char concentration is also a valuable quantity for the modeller. A useful estimate of it can easily be obtained by weighing samples collected by a char extraction probe. A detailed analysis of the gas species composition of a kind which can routinely be obtained with gas chromatography is also rarely reported. Such information, however, is of particular assistance when assessing the validity of devolatilization and volatiles combustion models.

Lastly, coal furnace trials ought, ideally, to be supported by small scale back-up experiments on devices such as a conventional drop-tube furnace. In this case, for example, experiments could be performed on the same coal used in the tunnel furnace experiments in order to determine its

volatile release rate and char reactivity. Such information would greatly assist the modeller in isolating the causes of poor prediction performance. It is also worth mentioning that the collection of precise cold-flow velocity data can be expeditiously executed on a scale model of the test furnace. These could be of real value, given the impossibility of making comparable hot-flow measurements in a larger scale furnace.

IMPERIAL COLLEGE VALIDATION STUDIES

The CANMET data have been used for validation studies at Imperial College. A previous set of data for bituminous coal (11) formed the basis for the very instructive validation exercise reported earlier (1). The present data, using the low- and high-volatile coals, have been employed in a validation exercise. This work is reported in a proprietary CANMET contract report (12). A publication for the open literature is in the course of preparation. It is considered that only a very short summary of the validation study is appropriate for inclusion in this paper, the primary intention of which is to report on the CANMET data set.

The computer code employed for this study is called MODTUN and is similar to that described previously (1). The gas phase computations are based on the TEACH code developed at Imperial College. The prediction procedures in MODTUN describe the flow, combustion and heat transfer in turbulent swirling pulverized coal flames. The mathematical formulation for these procedures applies the Eulerian conservation equations to the gaseous carrier phase. The particulate phase is described in the Lagrangian framework where representative particle flights are tracked through the prevailing gas field using a tracking procedure. The argument in favour of using the Lagrangian over the Eulerian formulation includes economy of computational and storage space and convenience in handling particle behaviour such as slip, drag, heat transfer, devolatilization and char combustion.

For the solid phase calculations, the particle motion and thermal balance equations are solved to obtain the particle histories of position, velocity, mass, etc., as it travels through the combustor. An efficient and computationally economic particle tracking routine has been developed to solve for the particle trajectories using a novel recurrence-relation type

solution scheme. The technique for handling the gas-particle interaction is termed the particle source in cell (PSIC) method where the influence of the particle on the gas phase is accounted for by source terms appended to the gas phase conservation equations (13). An approximate treatment for the turbulent dispersion of the particulate matter is incorporated; however, it should be noted that this is an area which generally needs further development.

For the gas phase computations, a fast and cost-effective solution algorithm called pressure implicit split operator (PISO) is used. A two-equation K-e turbulence model is also employed. The devolatilization process for the low-volatile coal is modelled by a simple one-step kinetics expression. Based on earlier work on bituminous coal (1), a multiple parallel reaction scheme is used to model the devolatilization of the high-volatile coal. For the volatiles combustion, a model is used which relates the rate of combustion to the rate of dissipation of eddies. The rate of reaction is then expressed in terms of the mean concentration of the reacting species, the turbulent kinetic energy and the rate of dissipation of this energy.

The thermal radiation transfer is handled by the computationally efficient non-equilibrium diffusion model of Gibb (14). This is a very economical procedure which, in a back-to-back test with an exact treatment, has been found to give good accuracy for the circumstances of the present furnace. Information about the absorption and scattering coefficients has been taken from Gibb and Joyner (15).

The char reactivity is taken to mean the reaction rate under the combined influences of pore diffusion and char chemical kinetics. This reactivity is modelled by a single step first order kinetics expression in which the frequency factor along with the activation energy are adjustable model parameters. External diffusion is accounted for separately and the rate of char combustion is governed by the combined reactivity and external diffusion processes.

Some representative predictions of the CANMET coal combustion experiments are given in Figures 12 to 21. Figures 12 to 16 show the predictions for the low-volatile experiments of combustion trial K and Figures 17 to 21 are those for the high-volatile combustion experiments of trial H. The aerodynamics of the near burner flow for the low- and

high-volatile experiments are shown in Figures 12 and 17, respectively. The near burner flow is shown here in the form of velocity streak lines at various axial locations in the burner exit and quarl regions. Figures 13 and 14 (low volatile), 18 and 19 (high volatile) show the predicted gas temperatures and oxygen concentrations at several stations compared with the CANMET data. The near axis discrepancy at the near burner station is considered to be due to an inadequate simulation of the rather complicated burner geometry. This is an area for further study. Figures 15 and 16 (low volatile), 20 and 21 (high volatile) show a comparison between the measured and predicted incident radiation and total fluxes at the cylindrical wall.

On the whole, it has been found possible to make reasonably satisfactory predictions of the CANMET data for both low-and high-volatile coals. A reasonable degree of predictive universality is observed for each of the three bituminous fuels and the two low-volatile fuels for which data have been collected. However, the physical modelling had to be altered in order to obtain a satisfactory simulation of the low-volatile coals. Both the devolatilization rate and char reactivity rate required modification. In particular, the good prediction of the low-volatile flames requires a high, so called, "Q factor". The Q factor is defined as the actual amount of volatiles released during furnace combustion normalized by the release determined in a proximate analysis. These findings are in broad agreement with those of Wall et al (4).

CONCLUSIONS AND RECOMMENDATIONS

A relatively large and extensive data package has been assembled for use with combustion prediction programs. The data consist of all the necessary input information required to simulate the conditions in the CANMET tunnel furnace facility. To validate the program predictions an extensive mapping of the velocity, temperature, major species concentration and heat transfer is also included. By using data packages such as this it is possible to study the various sub-models and empirical parameters used in the simulation of combusting flow fields.

This data package has been successfully used to validate a coal combustion simulation program developed at Imperial College. By comparing the output of the computer program with the measurements in the data

package, the appropriate sub-models and parameters were found. The resultant predictions are relatively good when compared with the measurements in the far field and agree with the findings of similar studies in the literature.

Whereas the data package was intended to be complete, there is much room for improvement. The first and most obvious is that there is a lack of measurements in the near burner region. As there is increased interest and computational ability in this region of the burner, it will be necessary to measure the field quantities closer to the exit of the swirl generator. The extraction of solid samples for analysis would greatly improve the understanding of char burn out and result in more accurate down stream predictions. A more accurate measurement of the gas composition in the combustion gases is needed to improve the understanding of the pyrolysis and combustion mechanisms in large scale combustion devices. Laminar flow, or drop-tube, experiments should be undertaken in parallel with the tunnel furnace experiments. These experiments would be useful in determining the fundamental laws and parameters used to model the pyrolysis and combustion of coal in the tunnel furnace studies.

REFERENCES

1. Lockwood, F.C., Rizvi, S.M.A., Lee, G.K. and Whaley, H. "Coal combustion model validation using cylindrical furnace data", 20th Symposium ((Intl) on Combustion, The Combustion Institute p 513-522, 1984.

2. Lockwood, F.C., Rizvi, S.M.A., Shah, N.G. "Comparative predictive experience of coal firing" Mech Eng Sci 200:C2:79-87, 1986.

3. Smith, P.J. and Fletcher, T.H. "A study of two chemical reaction models in turbulent coal combustion" presented at fall meeting, Western States Section, Combustion Institute, 1985.

4. Wall, T.F., Phelan, W.J. and Bortz, S. "Coal burnout in the IFRF No. 1 furnace", Combustion and Flame 66:137-150, 1986.

5. Smoot, L.D. and Smith, P.J., "Combustion and gasification of coal", Plenum Publishing Corp., N.Y., 1985.

6. Godoy, S., Hirji, K.A. and Lockwood, F.C. "Combustion measurements in a pulverised coal-fired furnace" Fluids Section Tech. Note FS/52/86, MED, Imperial College, 1986. Submitted to Combustion Science and Technology.

7. Hein, K. and Leukel, W. "Results of detailed measurements carried out in swirling pulverized anthracite flames during the series of trials C-13"; International Flame Research Foundation Report F 32/A/39; Sept. 1970.

8. McAskill, D.B. and Hallett, W.L.H. "Measurements of the flow field in the CCRL tunnel furnace at various swirl intensities"; CANMET Contract Report OST84-00015; Sept. 1984.

9. Tine, G. "Gas sampling and chemical analysis in combustion processes"; Advisory Group for Aeronautical Research and Development, North Atlantic Treaty Organization; Pergamon Press; London; 1961.

10. Truelove, J.S. "Prediction of the near burner flow and combustion in swirling pulverised-coal flames"; presented at 21st Int Symposium on Combustion, Munich, 1986.

11. Hughes, P. Private Communication, 1983.

12. Lockwood, F.C. and Rizvi, S.M.A. "Prediction of combustion performance of low-volatile Goodrich coal"; CANMET Contract Report 05Q84-00026, June 1986.

13. Migdal, D. and Agosta, V.D. "A source flow model for continuous gas-particle flow", J Applied Mechanics 34:860, 1976.

14. Gibb, J. Central Electricity Generating Board, Internal Note, MRM 85.

15. Gibb, J. and Joyner, P.L. "Liddell boiler reheater metal temperature: gas side heat transfer analysis", Report No. R/N/N1029, United Kingdom Central Electricity Generating Board, Marchwood Engineering Laboratories, 1979.

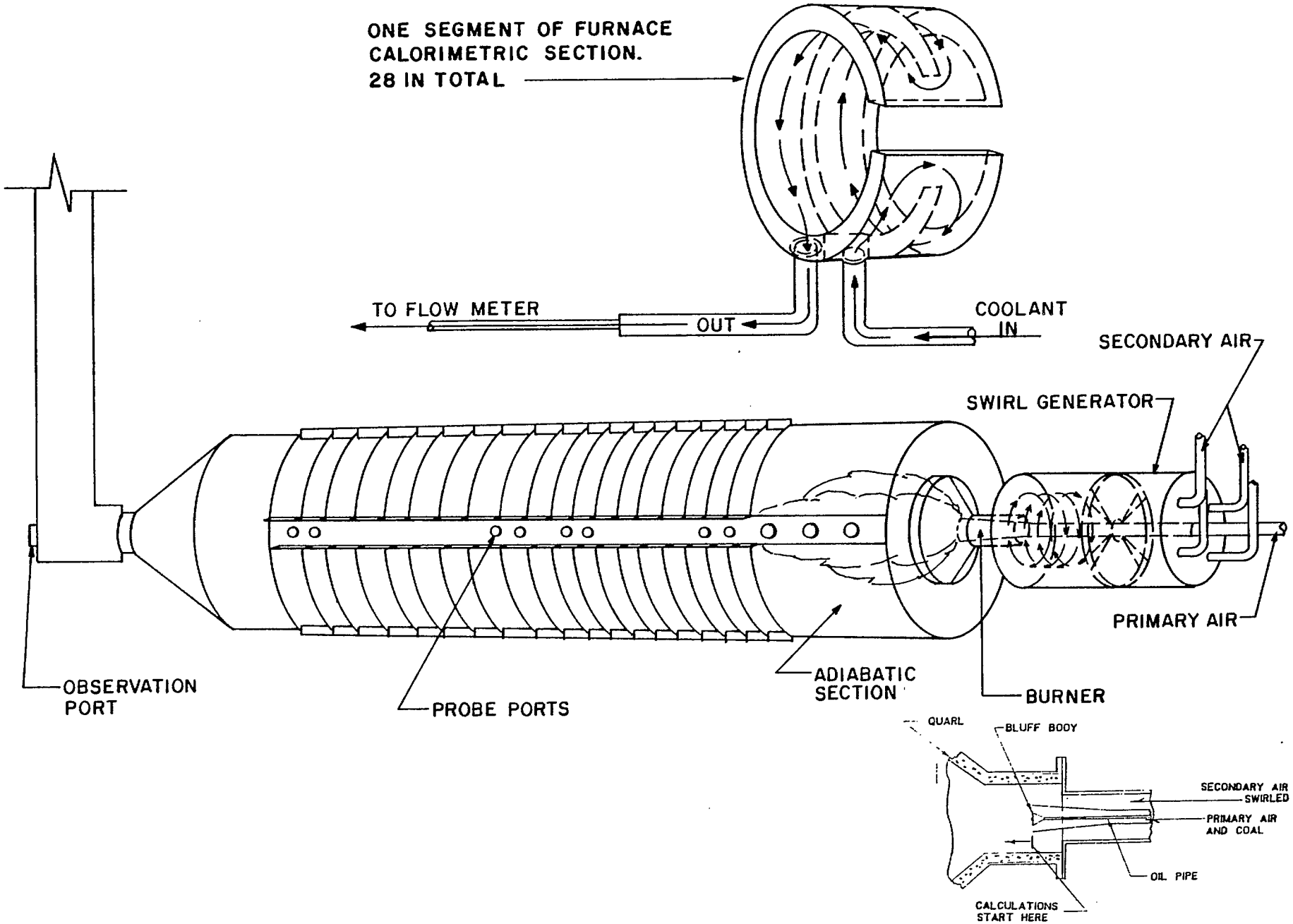


Fig. 1 - Schematic of the CCRL tunnel furnace facility

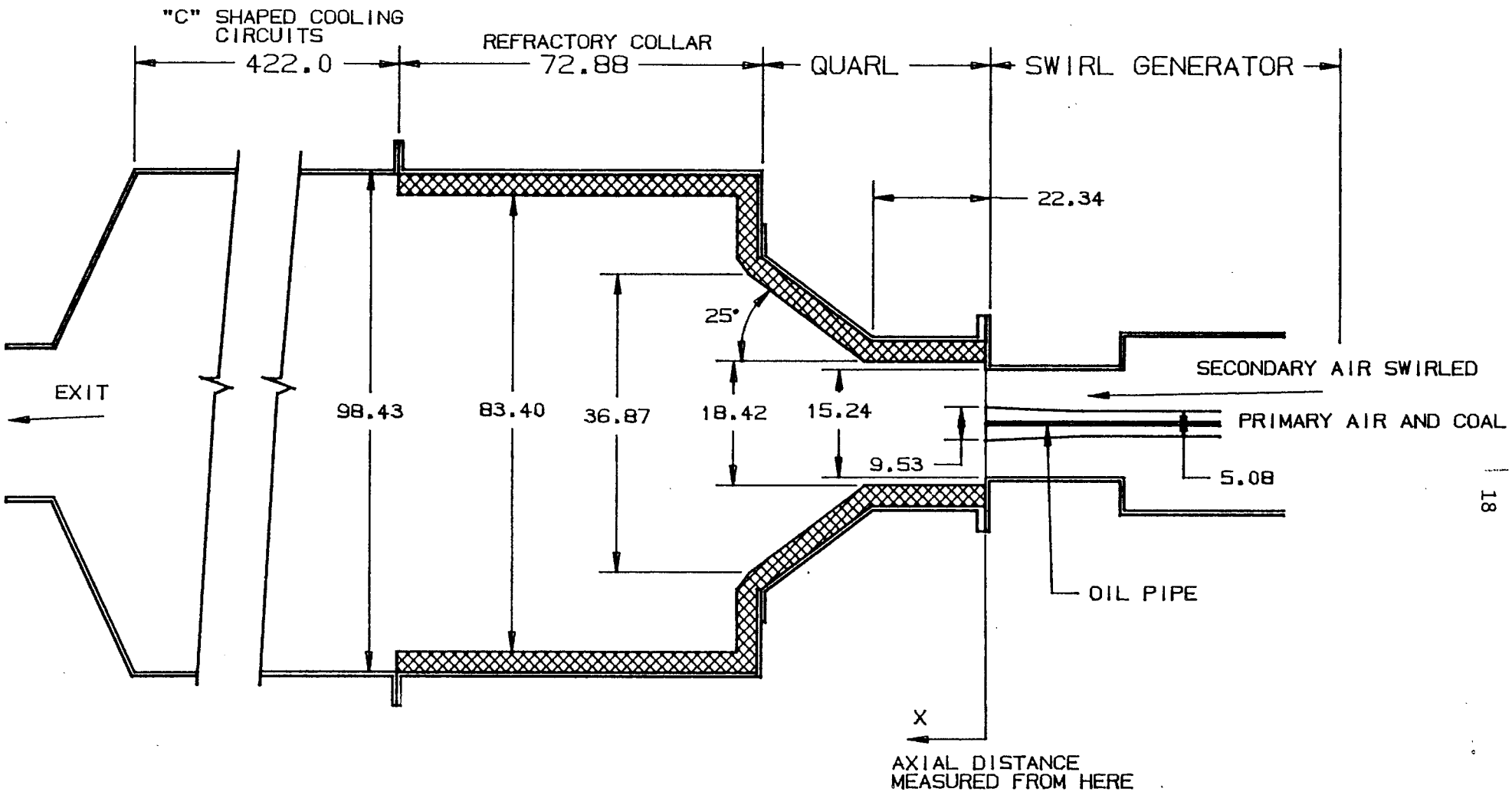
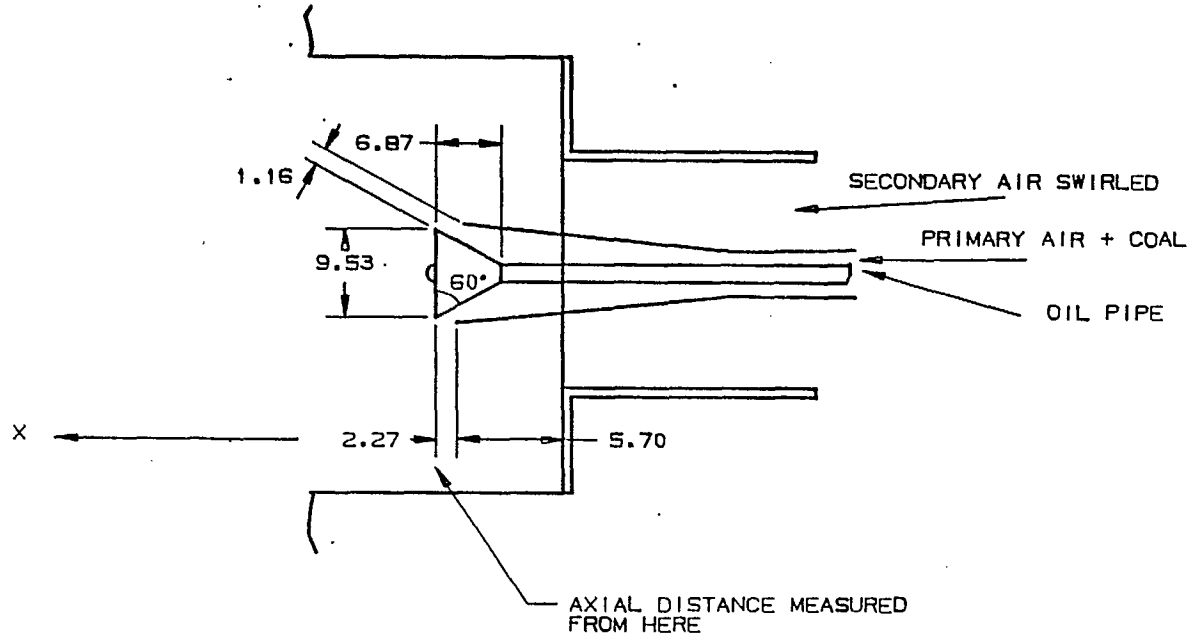
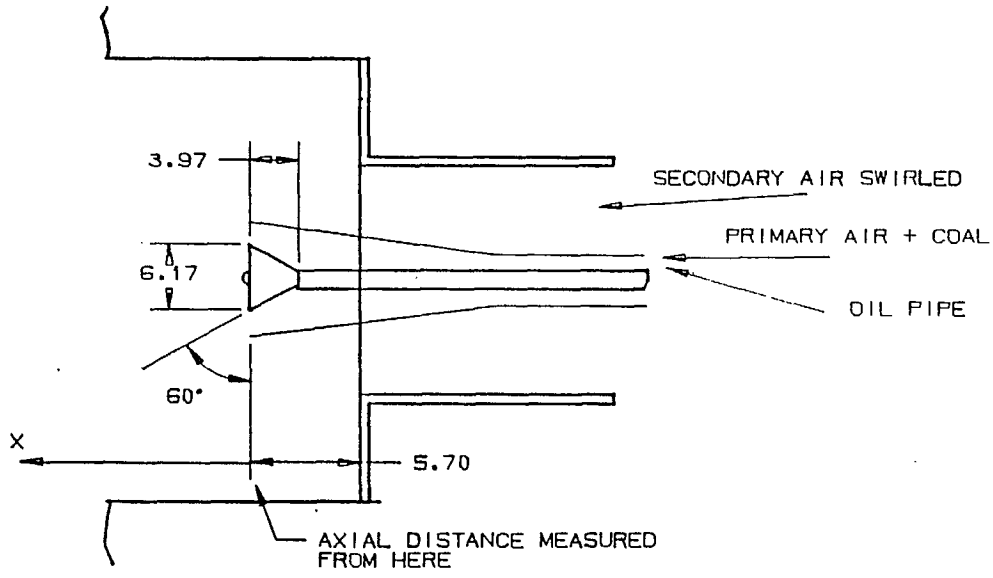


Fig. 2 - Schematic of the interior of the CCRL tunnel furnace



a)



b)

Fig. 3 - Schematic of the entrance region for the experiments using bluff bodies: (a) long bluff body (b) short bluff body

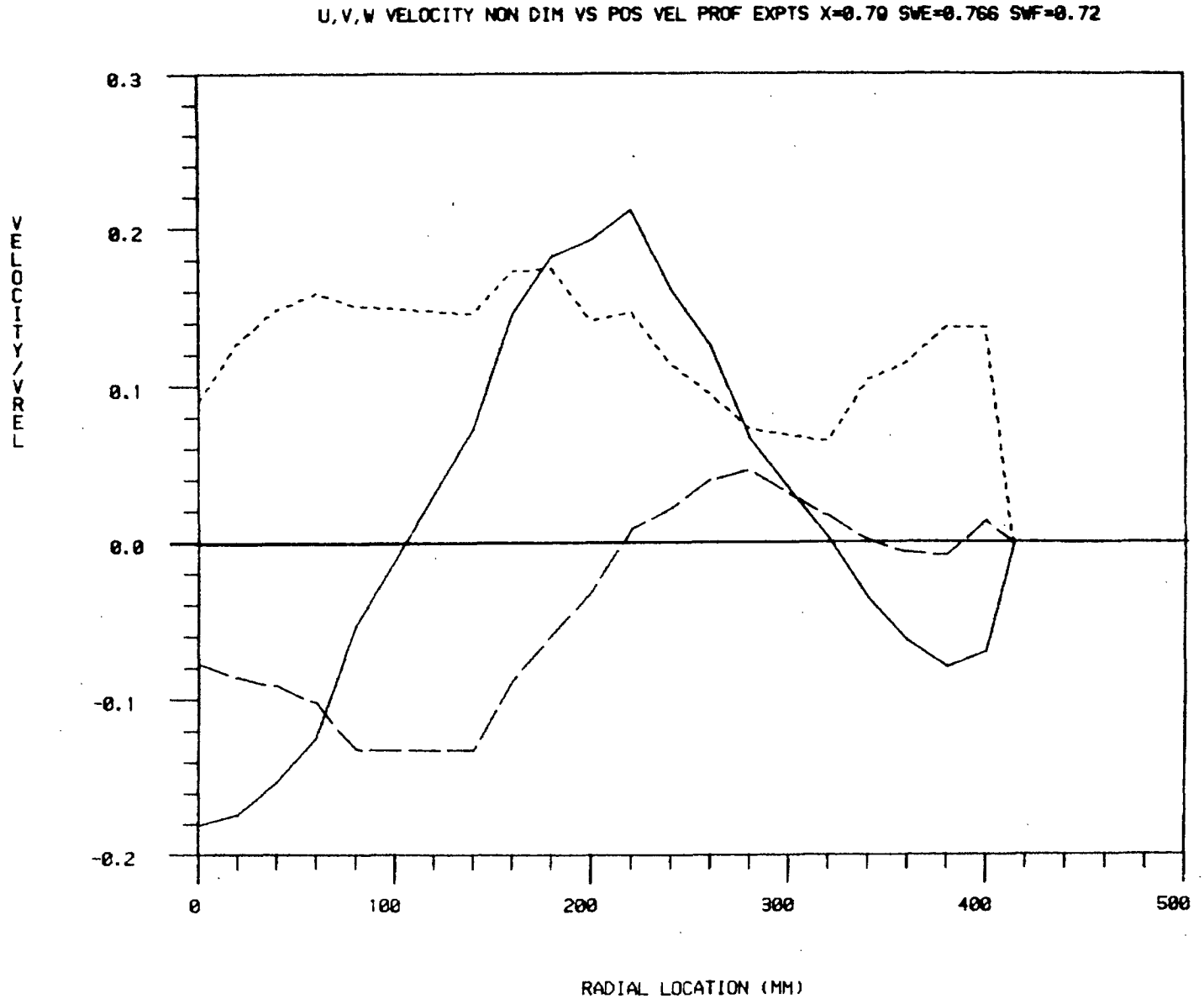


Fig. 4 - Typical non-dimensional velocity profiles in the tunnel furnace: solid u component, dash v component, dot w component (x = 0.79 m, swirl number at exit = 0.77 at sample location = 0.72)

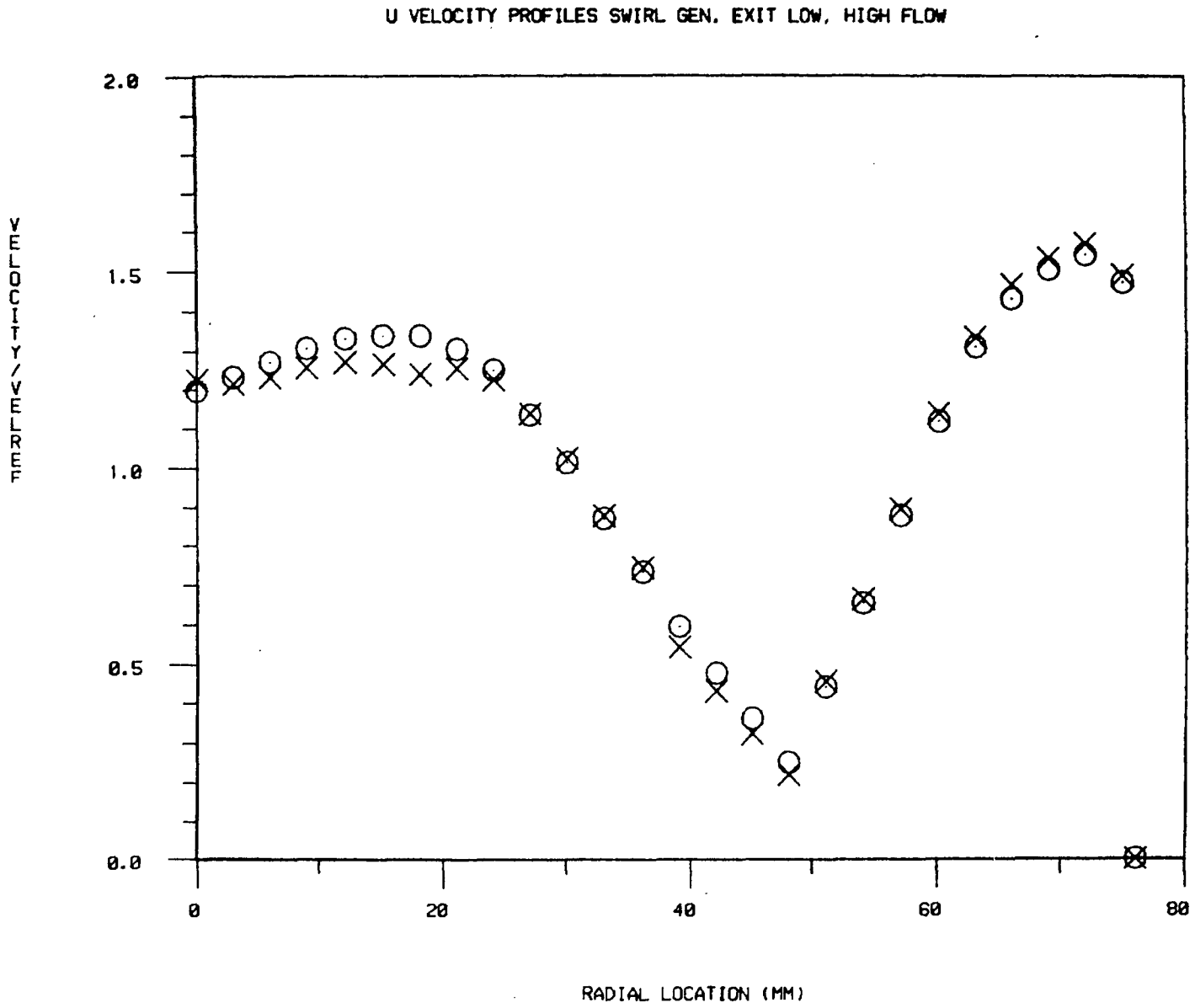


Fig. 5 - Typical measured non-dimensional u velocity profile at two total air flowrates: X low, O high (x = 0.0 m, swirl number = 0.802, 0.759)

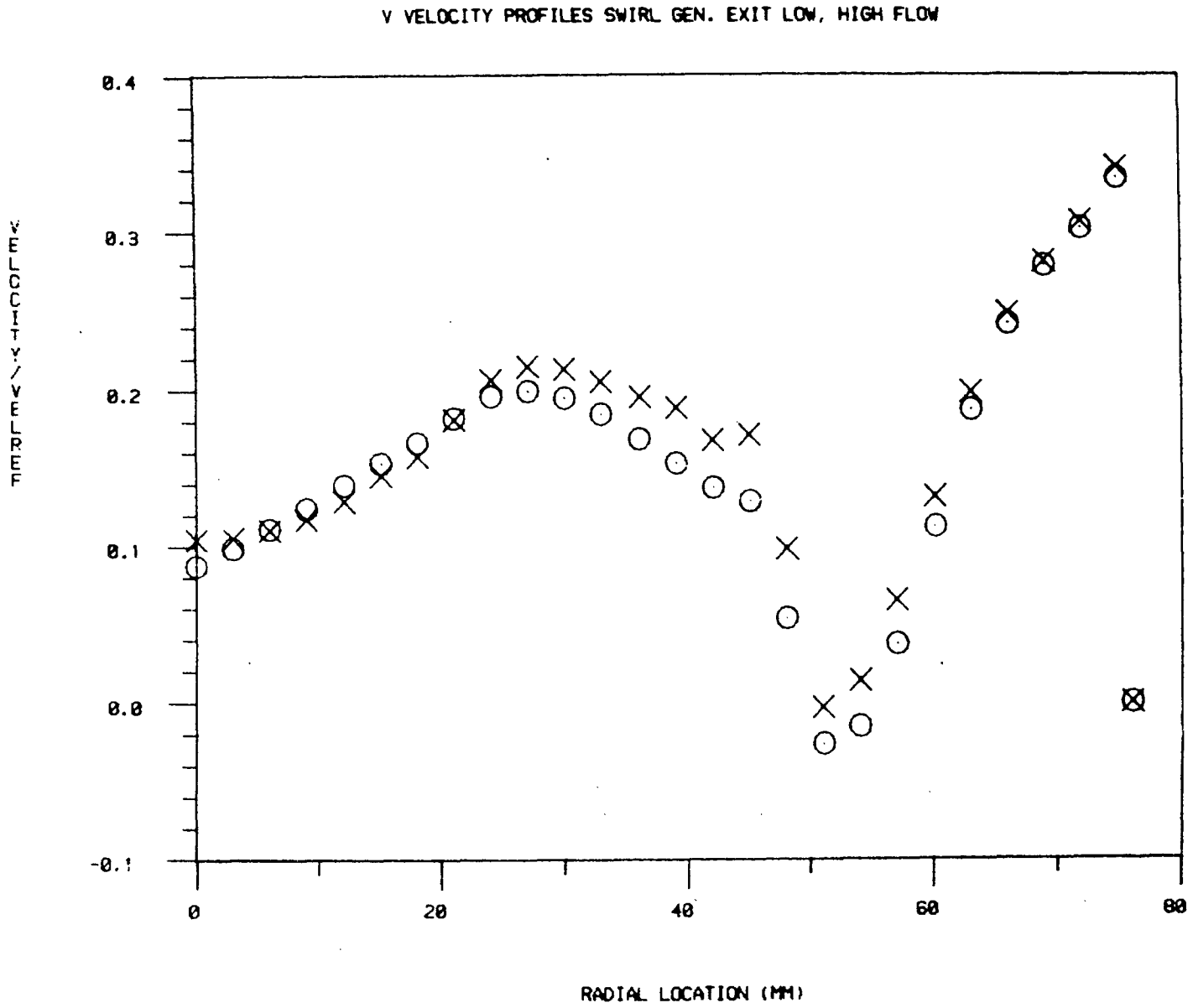


Fig. 6 - Typical measured non-dimensional v velocity profile at two total air flowrates: X low, O high (x = 0.0 m, swirl number = 0.802, 0.759)

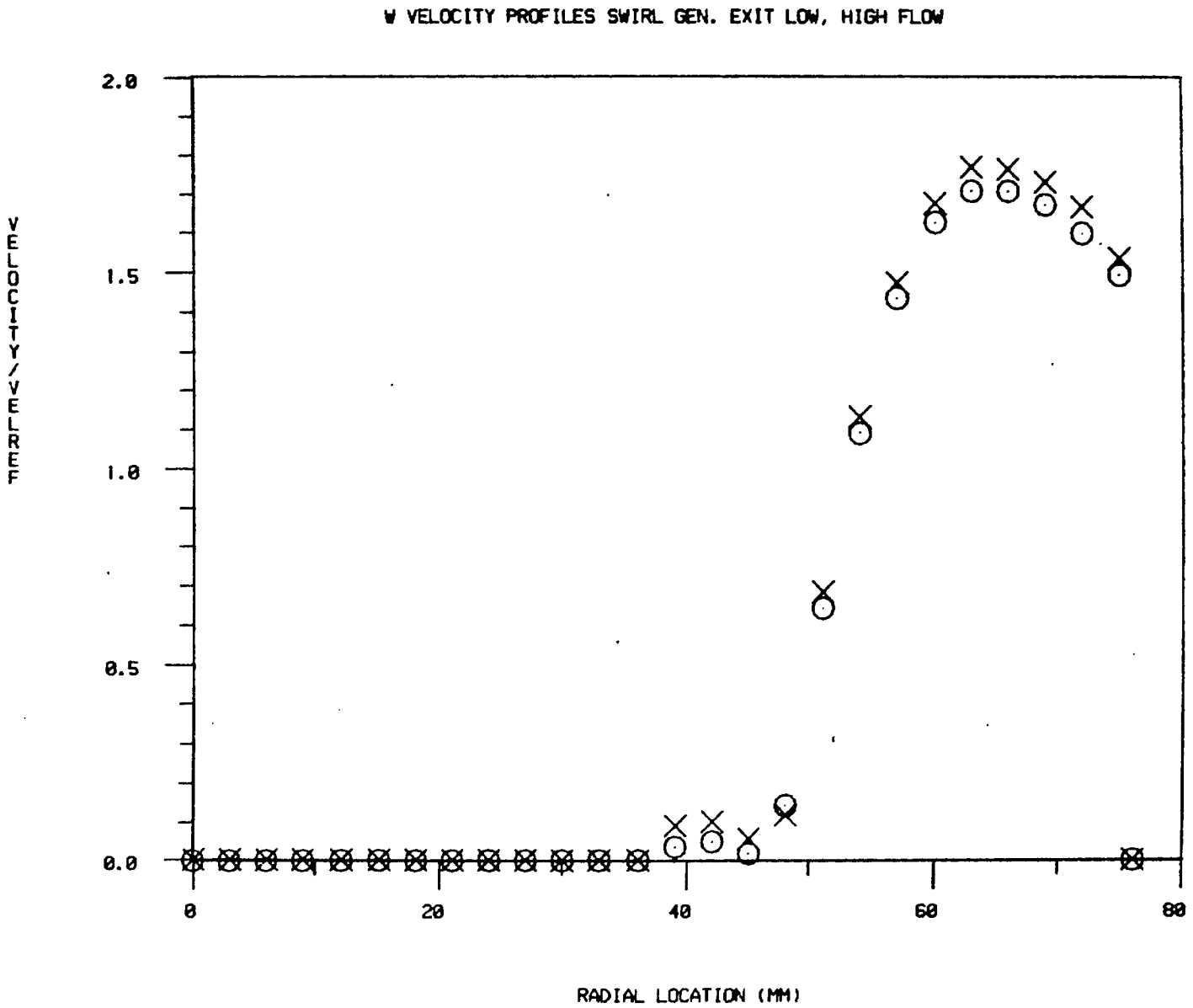


Fig. 7 - Typical measured non-dimensional w velocity profile at two total air flowrates: X low, O high (x = 0.0 m, swirl number = 0.802, 0.759)

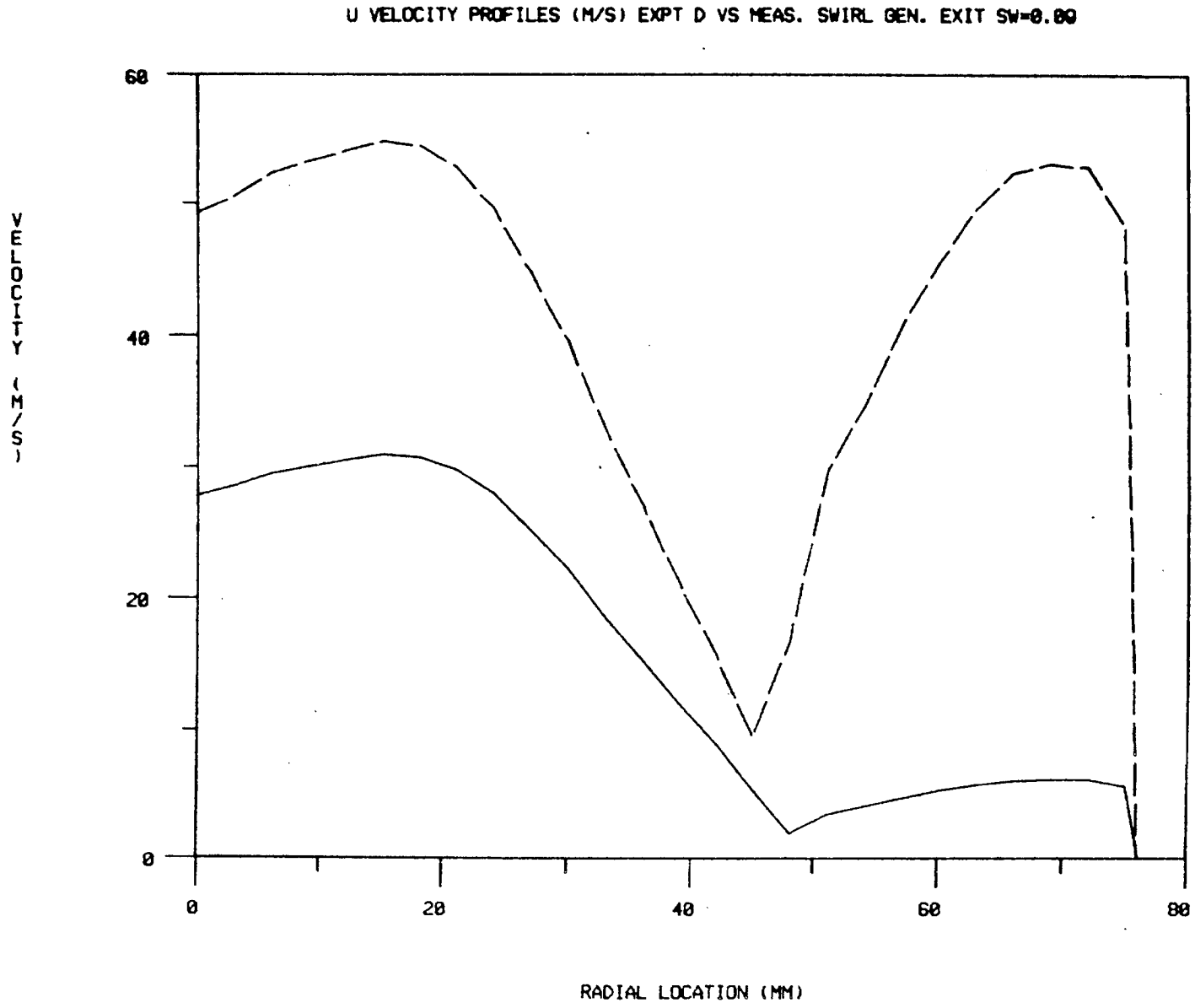


Fig. 8 - Comparison of measured u velocity profile (dash) to that computed for a combustion trial without a bluff body (solid) (combustion trial D)

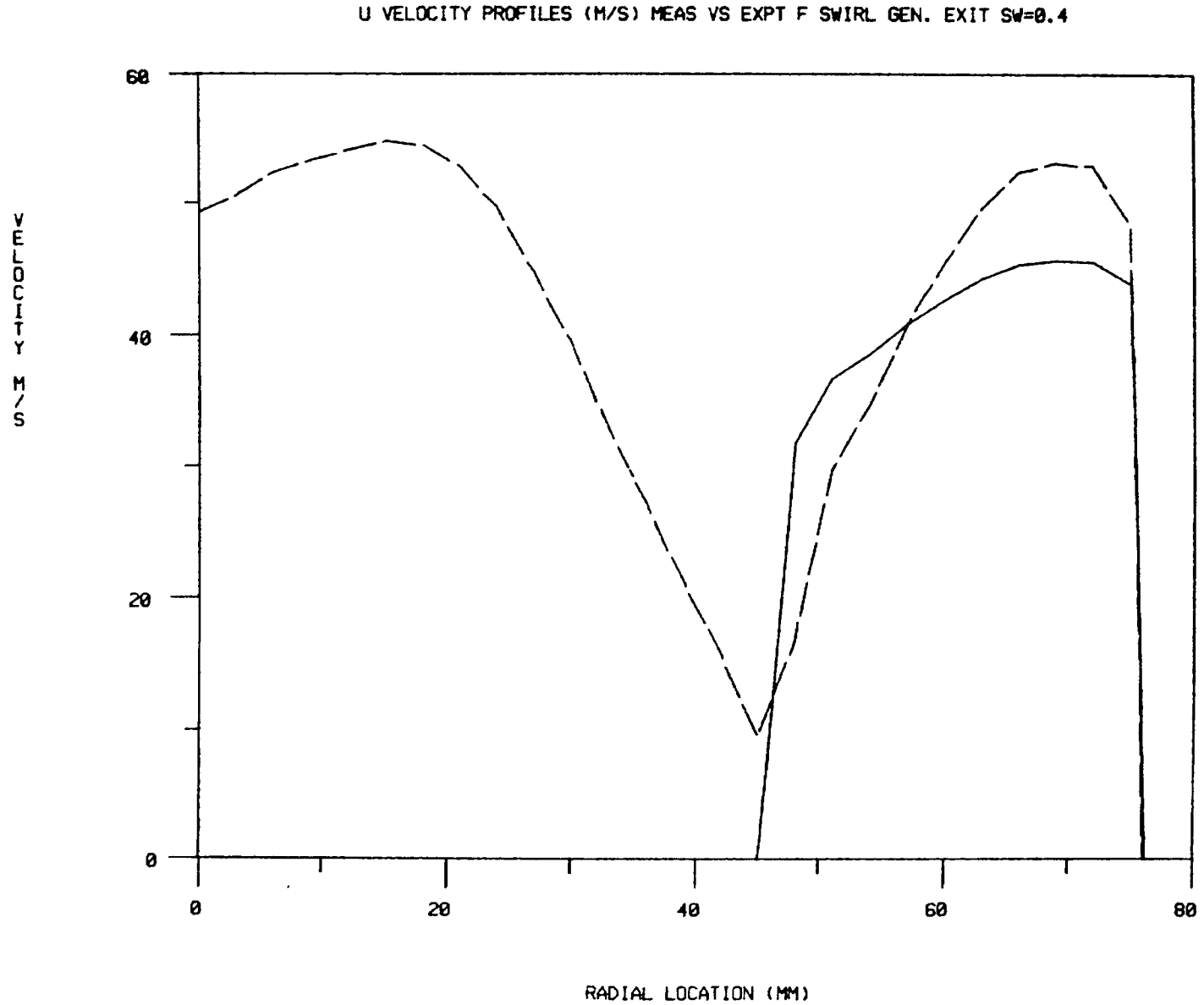


Fig. 9 - Comparison of measured u velocity profile (dash) to that computed for a combustion trial with the long bluff body (solid) (combustion trial F)

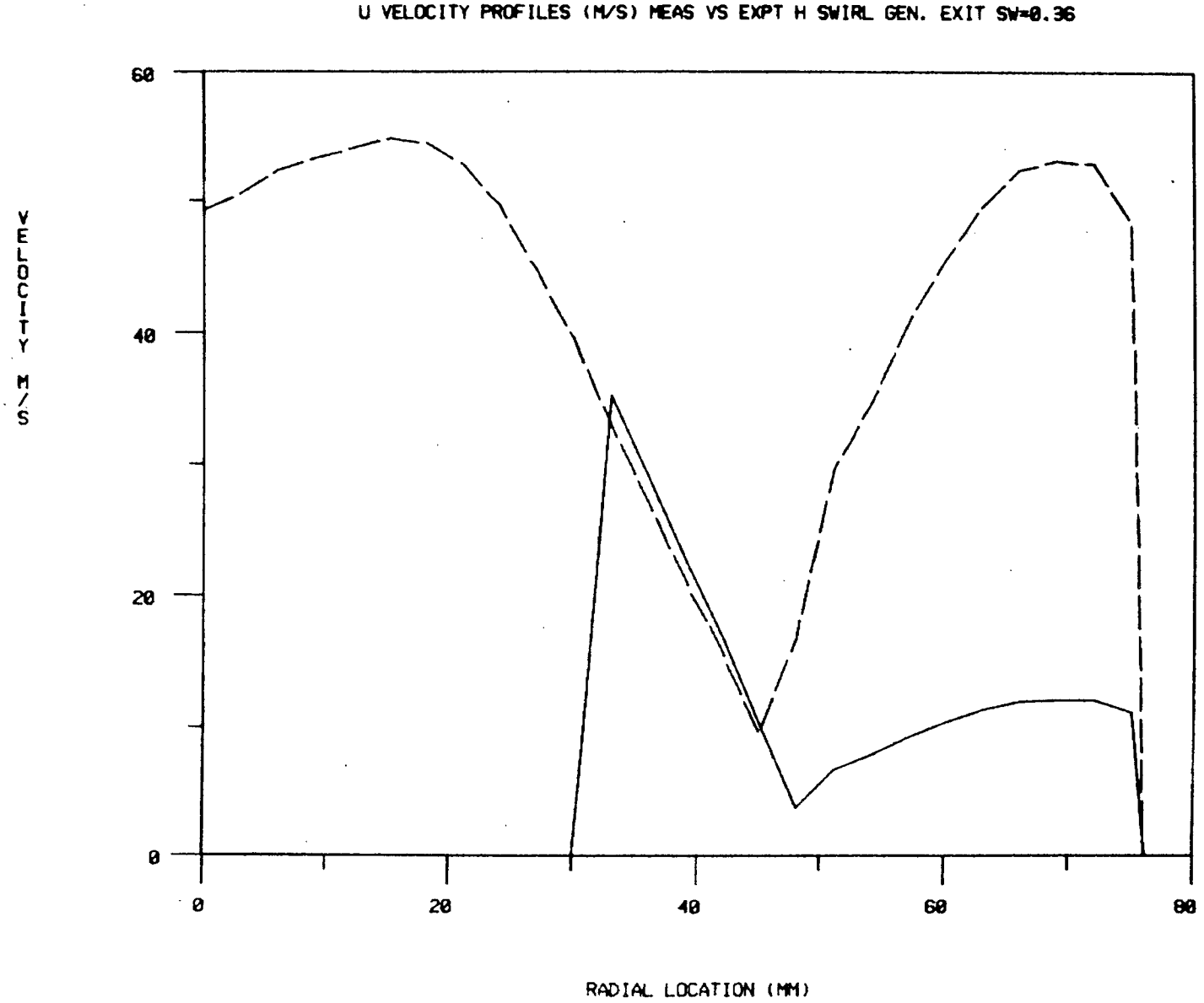


Fig. 10 - Comparison of measured u velocity profile (dash) to that computed for a combustion trial with the short bluff body (solid) (combustion trial H)

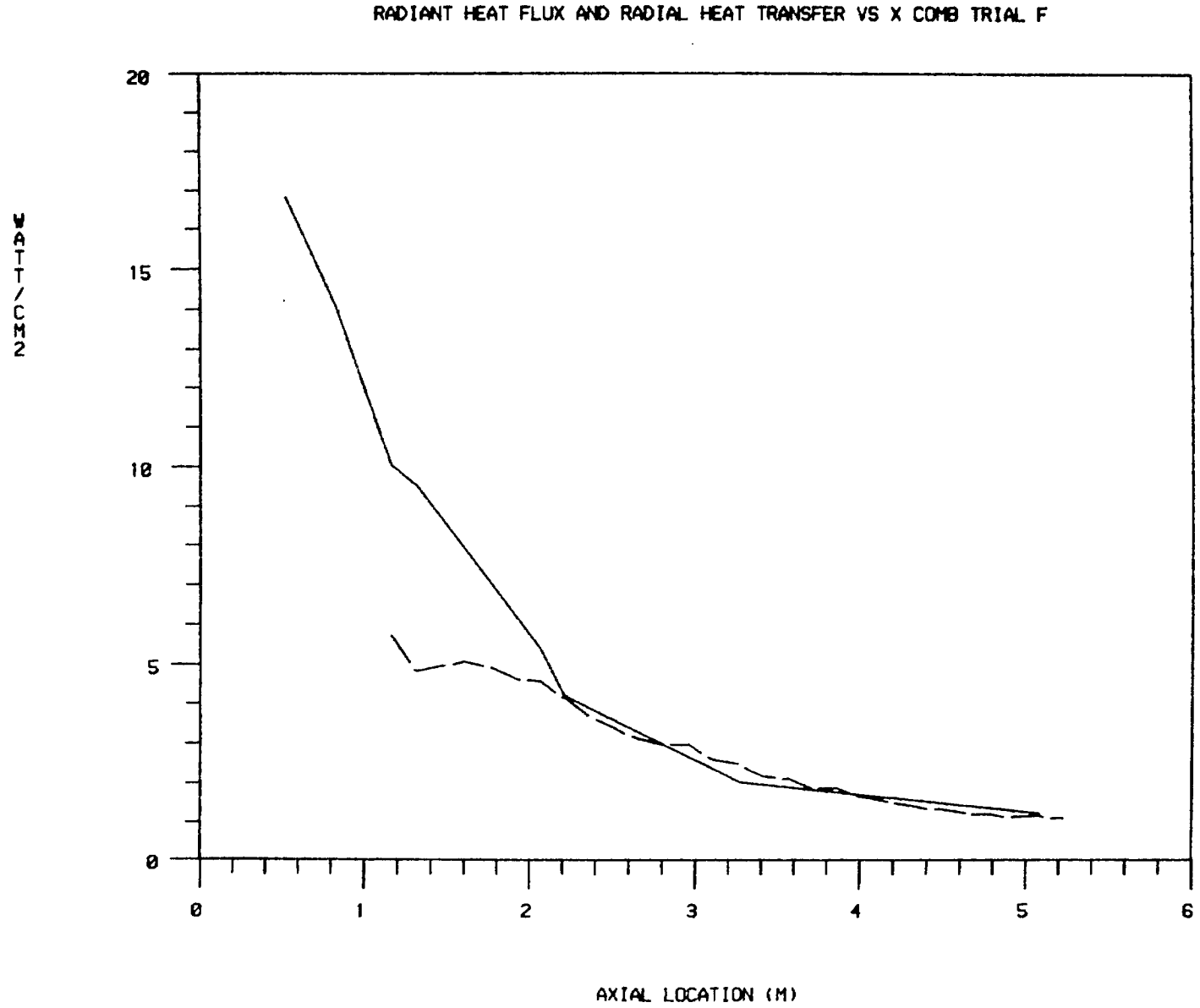


Fig. 11 - Typical combustion measurement showing the axial variation of total (dash) and radiated (solid) heat flux (combustion trial F)

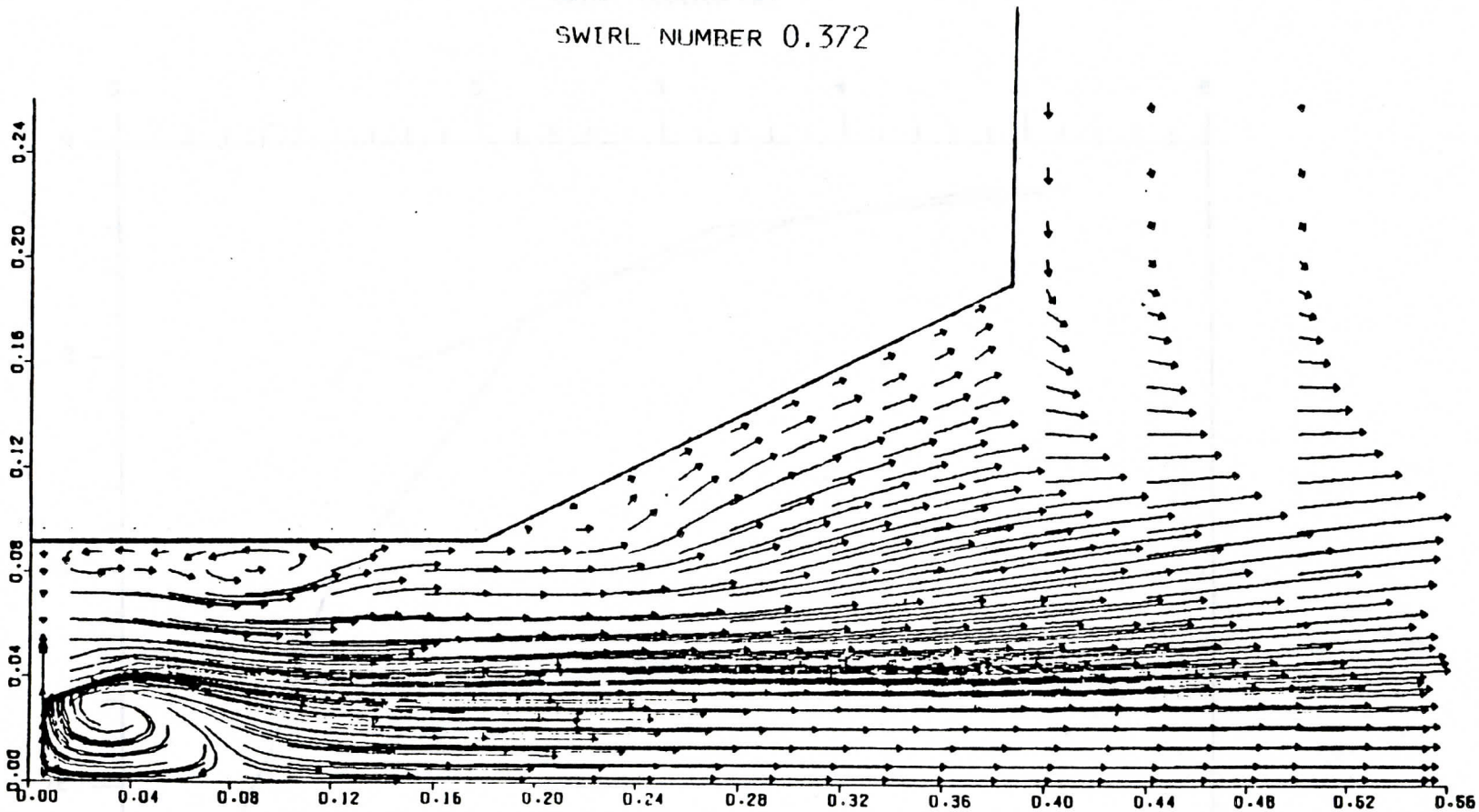


Fig. 12 - Computed streak velocity diagram of the near burner region for combustion trial K

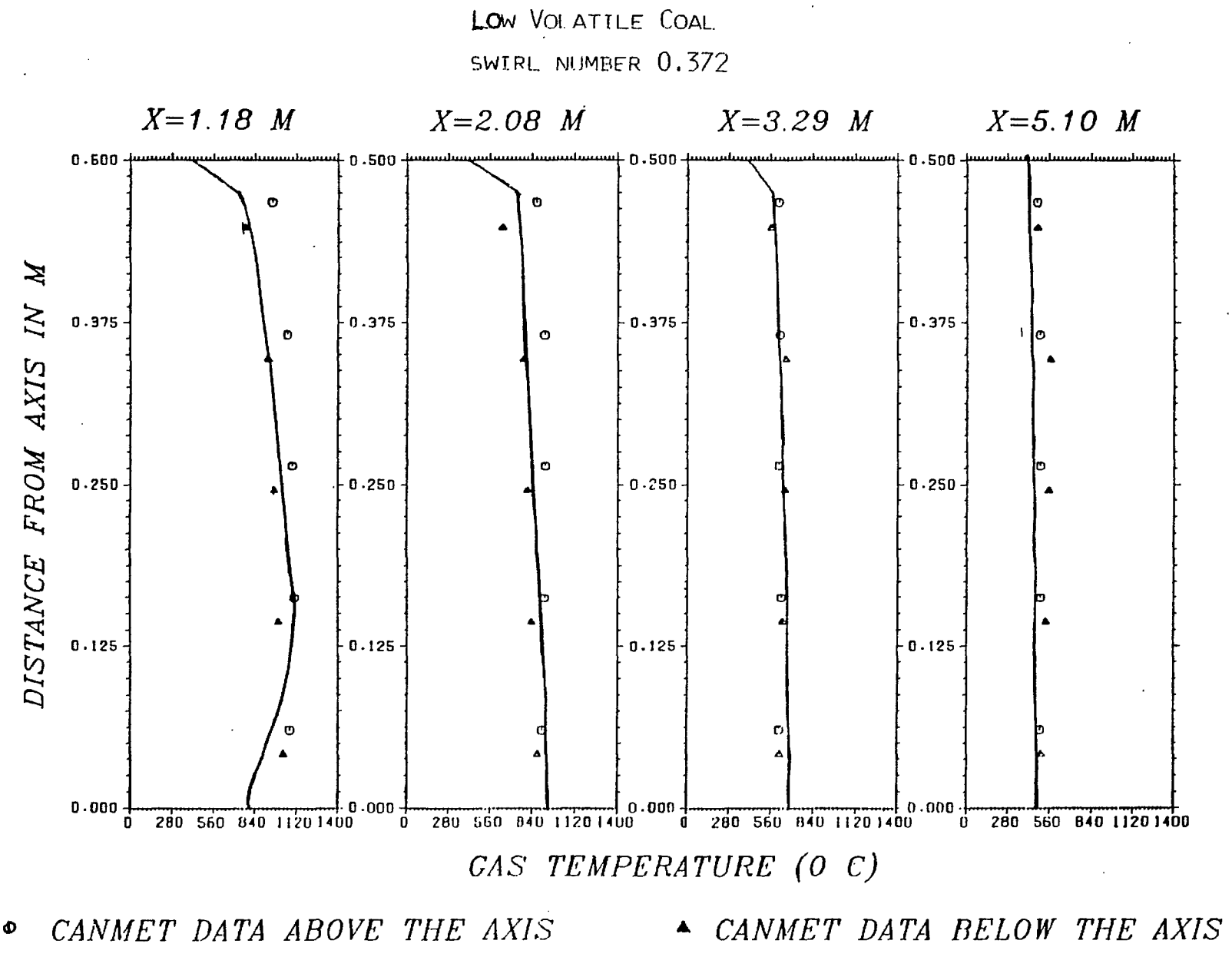


Fig. 13 - Comparison of the computed temperature profiles with that measured (combustion trial K)

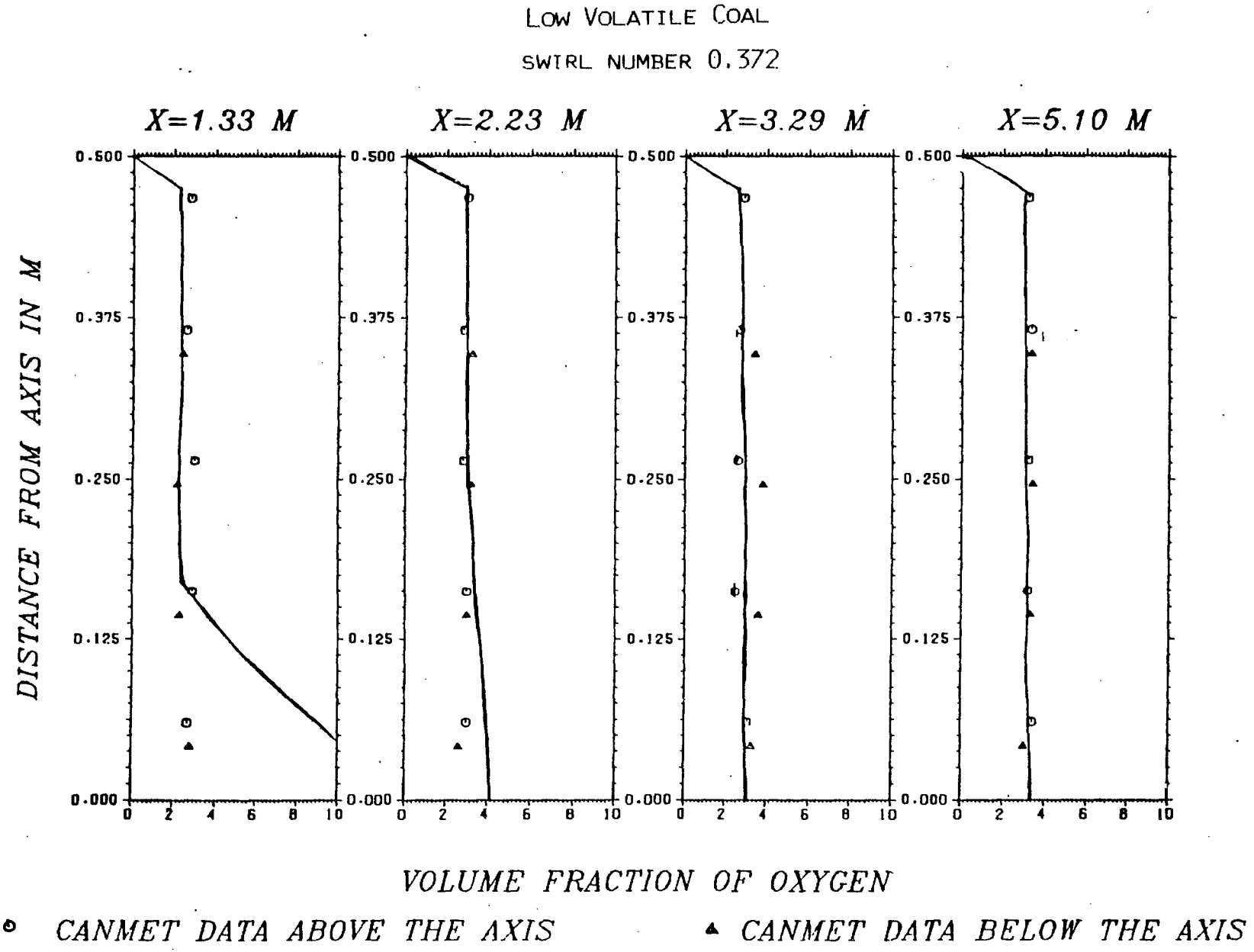


Fig. 14 - Comparison of the computed oxygen concentration profiles with that measured (combustion trial K)

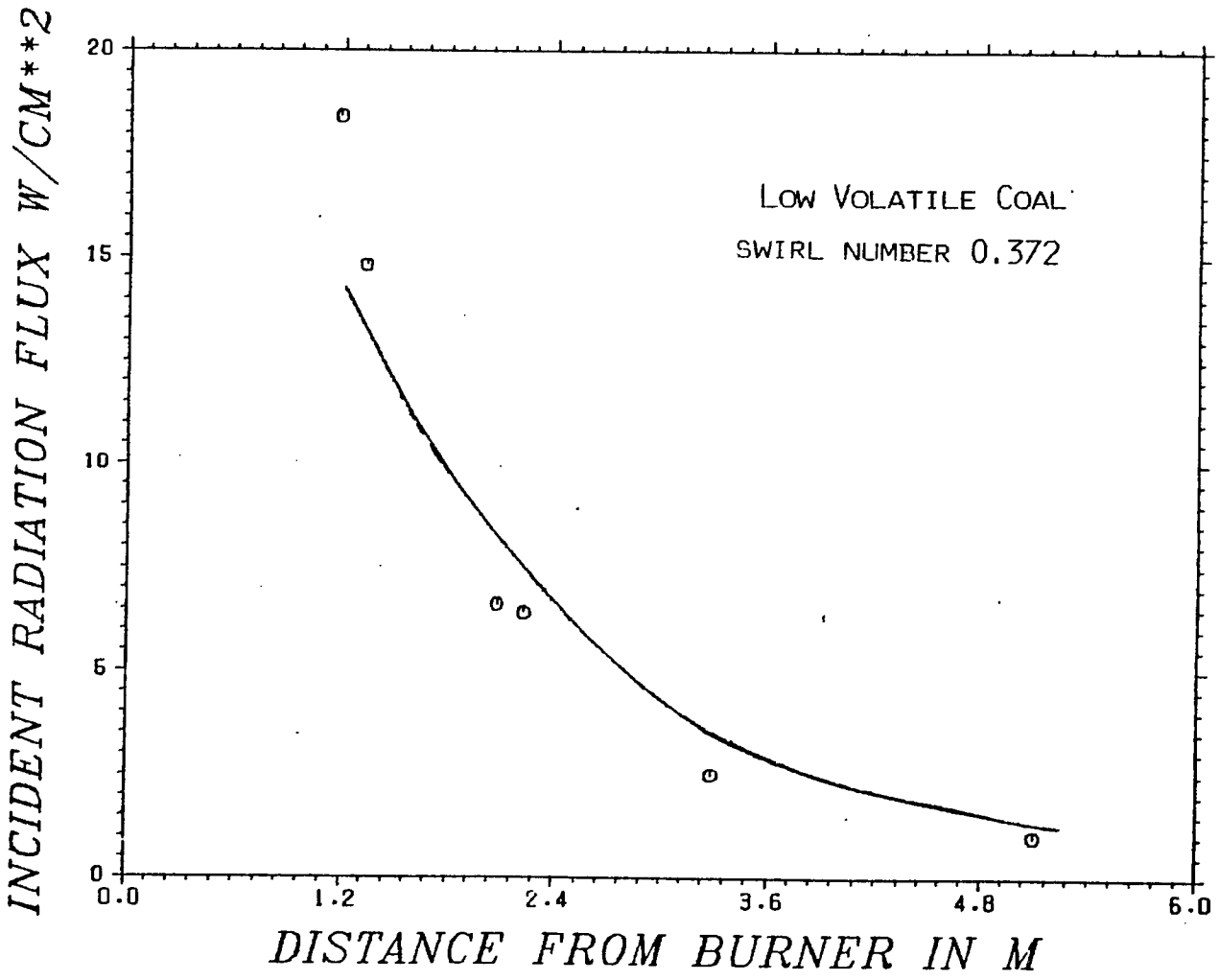


Fig. 15 - Comparison of the computed incidental radiation profiles with that measured (combustion trial K)

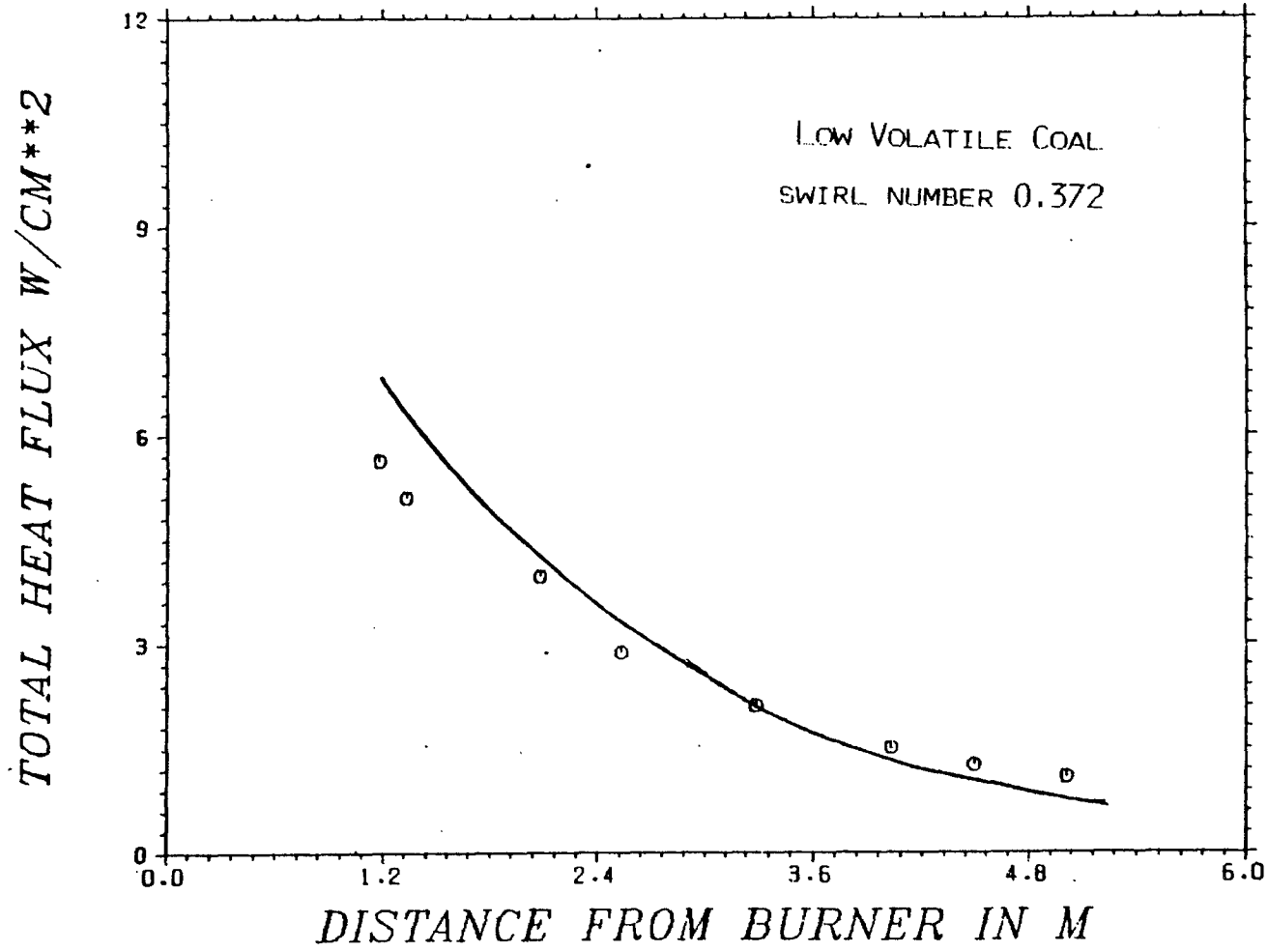


Fig. 16 - Comparison of the computed total heat flux profiles with that measured (combustion trial K)

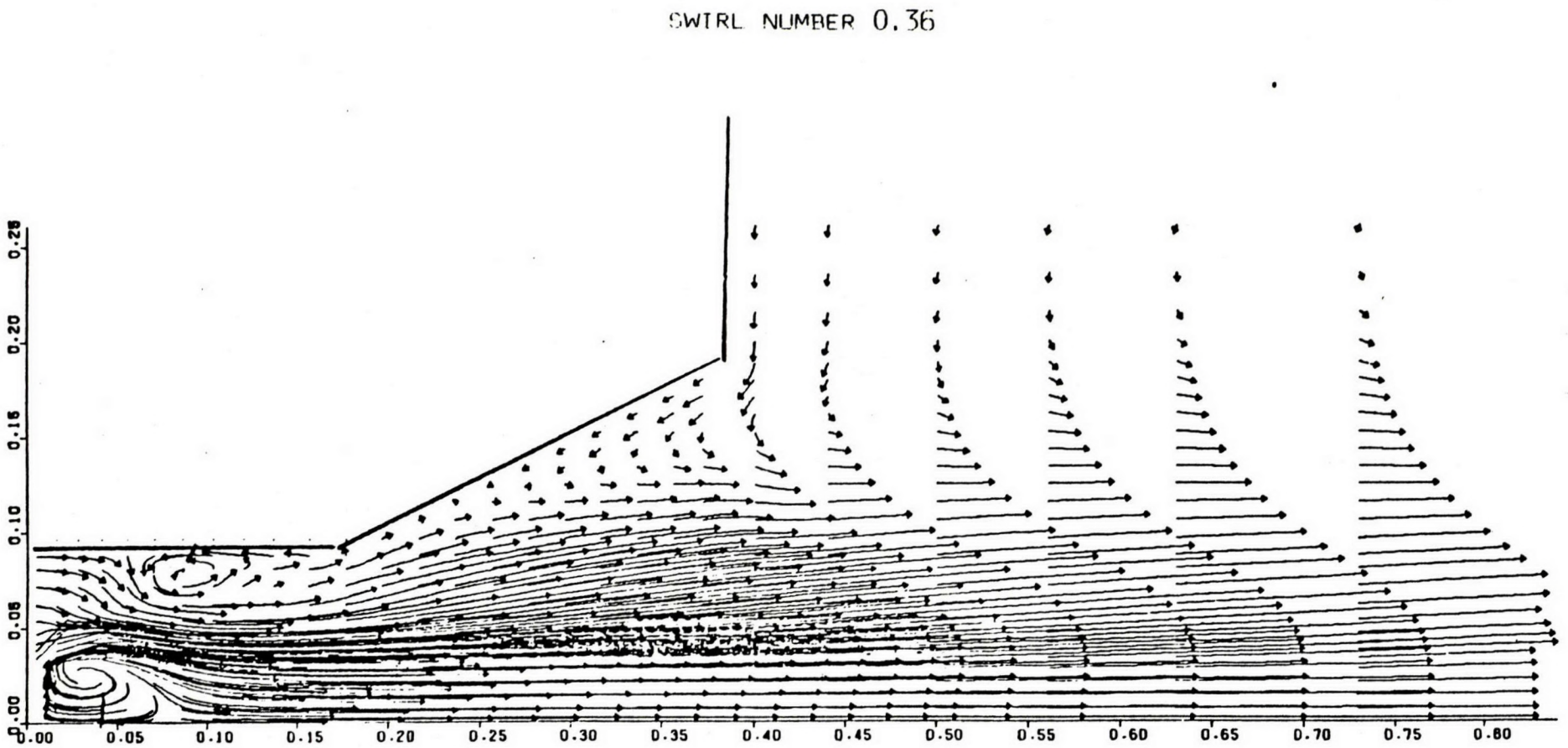


Fig. 17 - Computed streak velocity diagram of the near burner region for combustion trial H

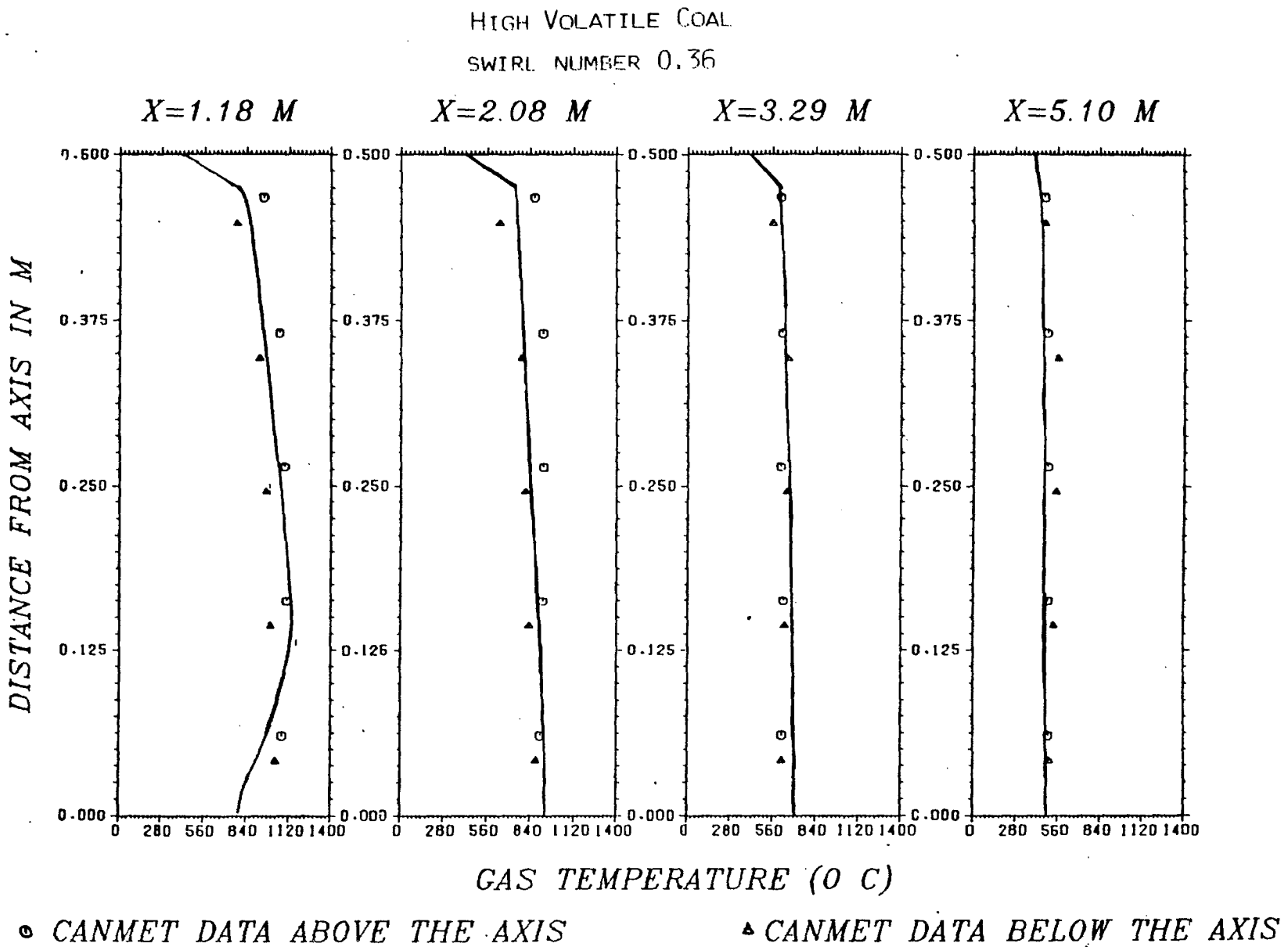


Fig. 18 - Comparison of the computed temperature profiles with that measured (combustion trial H)

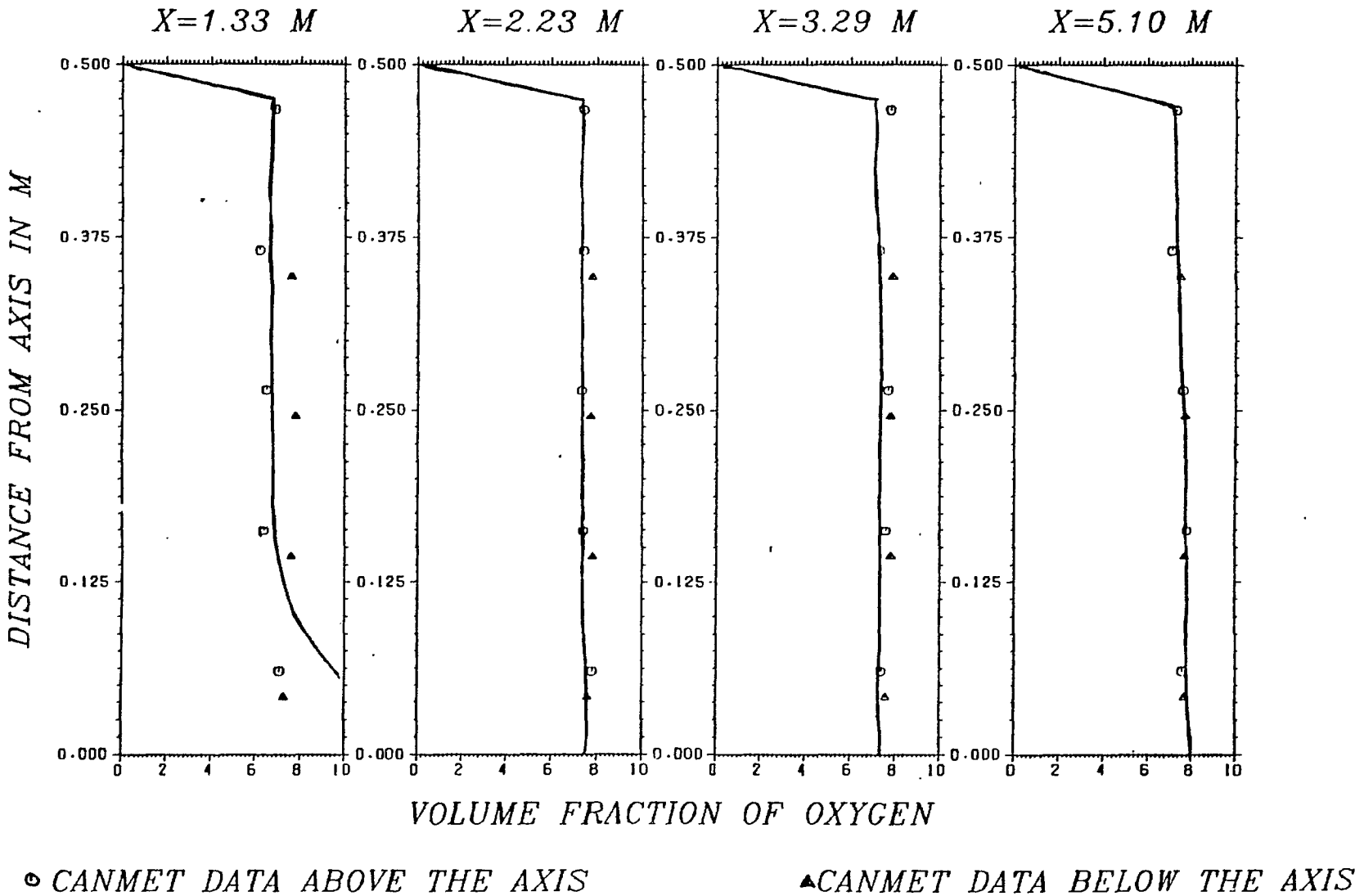


Fig. 19 - Comparison of the computed oxygen concentration profiles with that measured (combustion trial H)

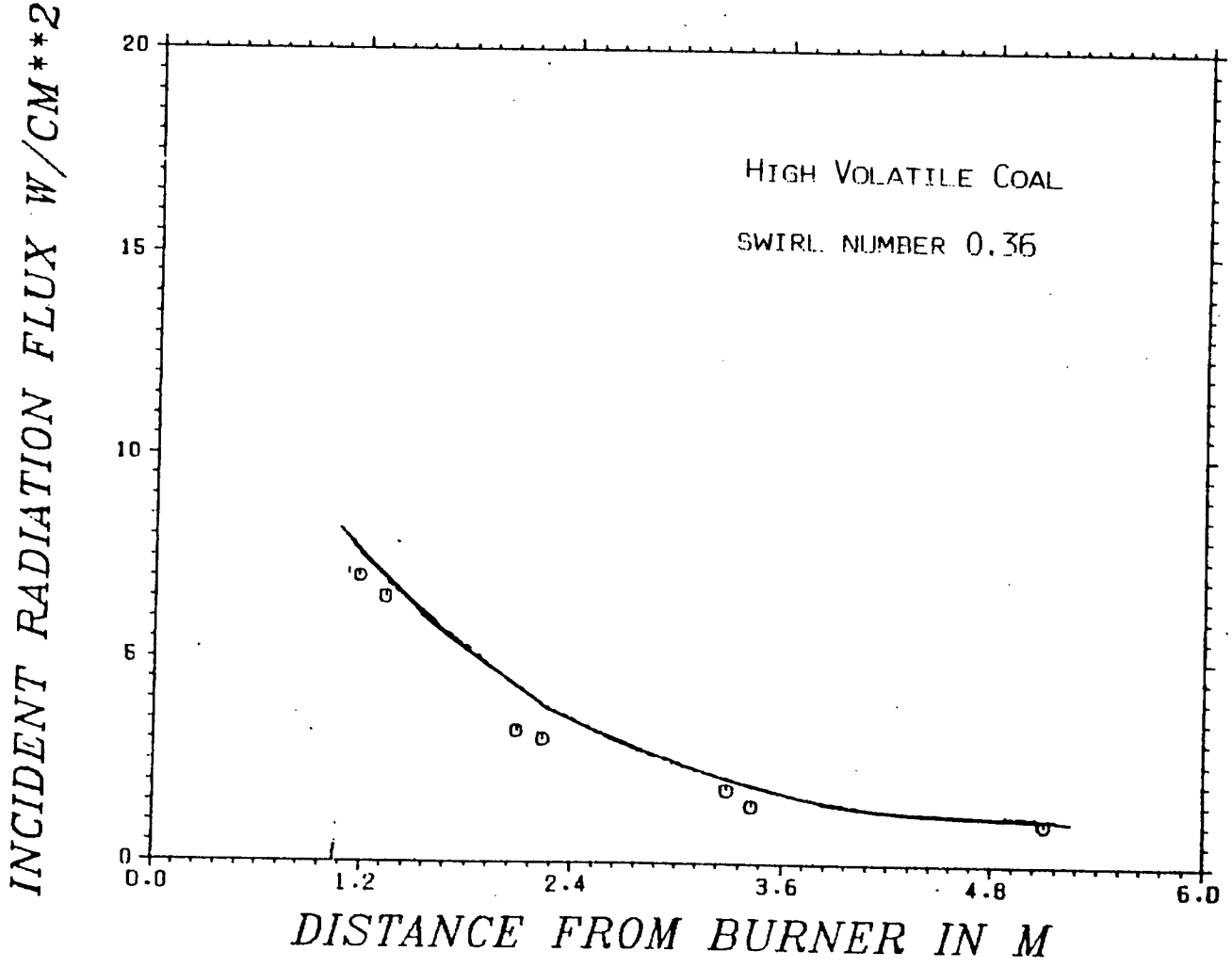


Fig. 20 - Comparison of the computed incidental radiation profiles with that measured (combustion trial H)

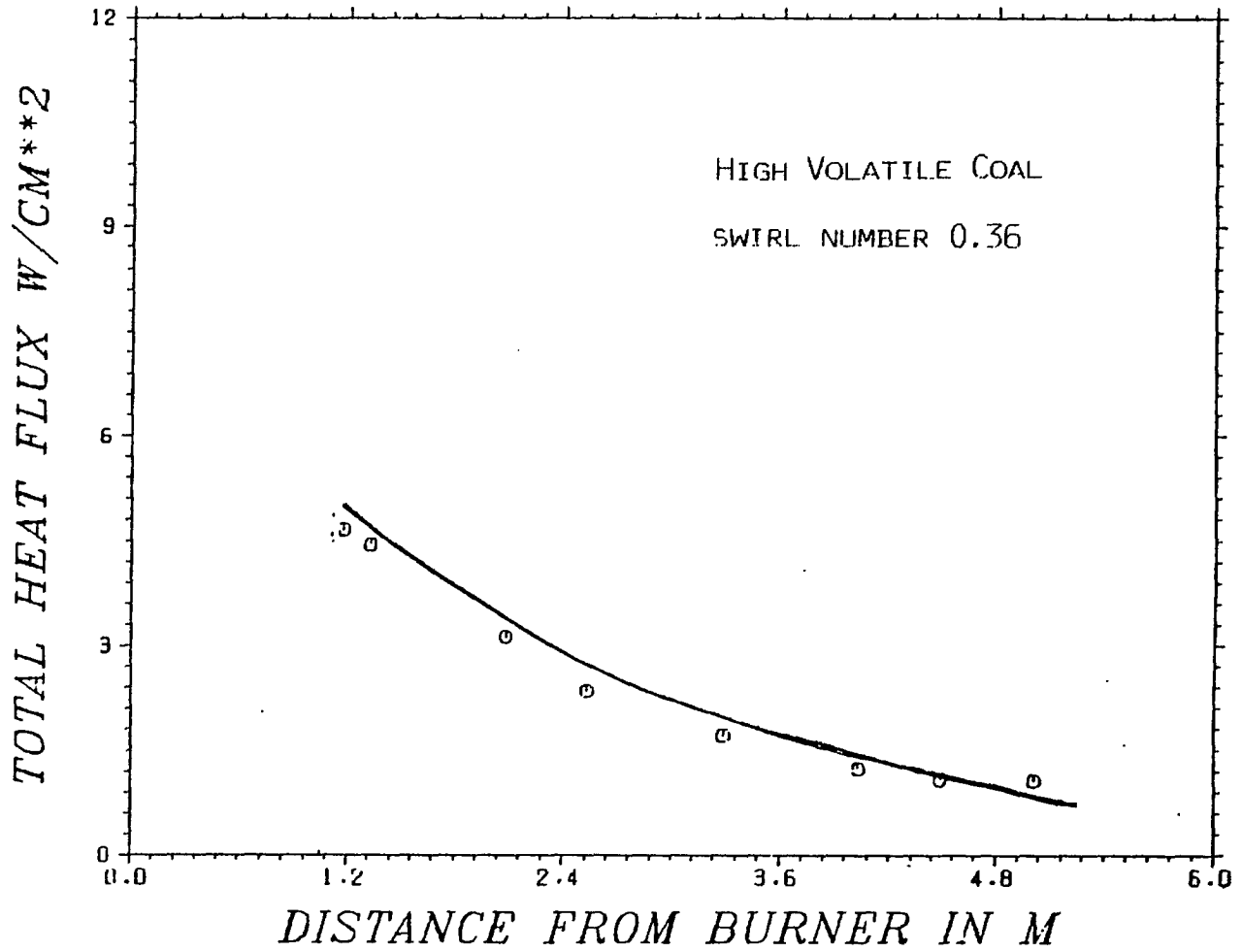


Fig. 21 - Comparison of the computed total heat flux profiles with that measured (combustion trial H)