FLOW CONDITIONS IN A GAS METERING STATION

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Paper 3.1

NORTH SEA FLOW MEASUREMENT WORKSHOP
26-29 October 1992

NEL, East Kilbride, Glasgow

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SUMMARY

This paper focuses on the ability for computational models to predict the decay of asymmetries in axial velocity profiles in long straight pipes. In the design of gas metering stations this is an important parameter since it influences the required upstream straight lengths. Asymmetries are typically generated by bends or by sharp-edged tees. In this presentation we consider asymmetries with the latter origin, exemplified by the geometry of a gas metering station. Experimental data were retrieved from a scale model of the geometry. Numerical simulations have been performed using both the k-ε model of turbulence and the more advanced non-isotropic Reynolds stress turbulence model (RSTM). The results show clearly that the k-ε model is the RSTM superior in engineering applications of the kind presented in this paper at the present state of development. This is not to say that the k-ε model attains the desired accuracy - it gives too low decay rate for asymmetries generated by a sharp-edged tee.

1. INTRODUCTION

To predict geometry-related installation effects on orifice meters, three-dimensional simulation models of the flow field in typical piping components as bends, combinations of bends, headers, straight pipes and orifice meters have been developed and tested. The commercial fluid dynamics computer program Phoenics is used to solve the Navier-Stokes equations. The solved equations have been presented by Rosten and Spalding[4] and will not be detailed here. A system, which we call Tandem, has been developed to enable the description of a complex piping arrangement using these standard components. This system automatically transfers the interface flow conditions between the individual components in a sequence. The Tandem system was described and its use was exemplified at the 1990 Installation effects on flow metering seminar at NEL through the presentation of Thomassen and Langsholt [1],[2].

The main objective in developing Tandem was to be able to predict the actual discharge coefficient for orifice meters in metering stations of different geometrical design. Provided a high degree of accuracy can be achieved in this kind of simulations, we have established a useful tool for detailed flow studies of the effect of piping layout in new gas metering stations as well as for modification of old metering stations.

2. THE GAS METERING STATION

2.1. Geometry

The metering station is displayed in Figures 1 and 2. It has four meter runs, all with an internal diameter of 325mm. The header to meter run diameter ratio is 1.32. Upstream of the manifold is a twisted S-bend. 30 D of straight pipe separates the S-bend and the first branch-off from the manifold. Upstream of the S-bend is more than 200 D of straight pipe.

A question that is often raised is: Does the metering station comply with requirements given in ISO5167? One way of answering this question is to check the geometry against the required straight lengths given in the standard. This standard does not mention the manifold T disturbance explicitly, so one is left to interpret the standard at this point. In our mind, the layout does satisfy the standard.

Another method is to study whether the flow conditions satisfy the requirements given in ISO 5167 (1991) section 7.4. This section requires a swirl less than 2° and a deviation from fully developed velocity profile of less than 5%. Since no instrument has been available to measure the flow conditions on-site, mathematical simulations and scale model tests have been carried out.

2.2. Tandem simulation of the gas metering station

Figure 2 illustrates the geometry as it is defined for the Tandem simulator. A twisted S-bend of the kind preceding the manifold of the gas metering station is known to set up swirl in the flow. The distance between the two bends determines the strength of the generated swirl. The closer the bends, the stronger will the resulting swirl become.

Examination of the Tandem simulation results did show that with 3.5 D of straight pipe between the two bends in the S-bend combination the resulting swirl was weak. For all practical purposes it could be considered as dissipated after the next 30 D (branch off for the first meter run). Also the asymmetry in the axial velocity profile downstream of the S-bend, proved to 'die out' over these 30 D of straight pipe. The profile appeared near symmetric, although not being fully developed.

Altogether this means that the upstream geometry to the manifold of the gas metering station, i.e., primarily the S-bend, is of little influence to the conditions in the meter-runs. Further, since the manifold and the meter-runs all lie in one plane, the horizontal plane, one will not experience swirl of solid body type in the meter-runs. This was observed in the simulation work, but will not be presented here.

Since the flow situation is very similar in all the meter-runs we will limit the detailed results to be presented for meter-run B only. In these high pressure simulations we monitored the solution in cross-sections 6.8 D, 32.3 D and 50 D into the meter-runs. Figure 3 shows the non-dimensional axial velocity profiles along the horizontal diameter in these 3 cross-sections. Figure 3 also includes the simulated fully developed turbulent profile, using the k-ε model of turbulence. The profiles are made dimensionless using the maximum axial velocity appearing along the same respective horizontal diameter.

As can be seen from Figure 3 the distinct asymmetry at 6.8 D is still significant at 32.3 D, and even after 50 D of straight pipe. The deviation from the fully developed profile was quantified using the definition given in ISO-5167[3], section 7.4. Due to the applied definition and the strong asymmetry simulated at 6.8 D, the maximum deviation in this position is as high as 25 %. According to the simulation result it is still in excess of 10 % at 32.3 D, but has come just below the 5 % limit set in ISO-5167 in the position 50 D from the header.

2.3. Consequences

The results showed that the velocity profiles did not fulfill the requirements of ISO-5167. The Tandem/Phoenics tool was, during the verification phase, tested against experimental data for a geometry similar to the metering station manifold. This test showed reasonable agreement between measurements and simulations, but it must be added that the measurements suffered from lack of accuracy. Therefore, when we faced the simulation results, we did not have complete confidence in them. Therefore, it was decided to build a Plexiglas scale model of the metering station and measure the profiles.

3. THE SCALE MODEL - EXPERIMENTAL WORK

The Plexiglas model was built in IFE's atmospheric air rig in the scale 1:2.85. Figure 4 shows a photography of the header and the meter-runs of the scale model. Atmospheric air was sucked through the meter station from a 30 D long pipe entering the scale model header. At the inlet to this pipe we mounted a perforated plate to avoid external disturbances. The flow entering the header exhibited a close to fully developed velocity profile. When running the tests, three out of the four meter-runs were in operation while one was closed. The Reynolds-number in the meter-runs was approximately $9 \cdot 10^4$, corresponding to an average velocity of 11.5 m/s.

3.1. Measuring devices and procedure

A pitot static probe was used to measure the velocity profiles while a cylinder pitot probe served as the measuring device for the swirl angles. At meter-run position 32.2 D downstream of the header (referred to the header center line) a special arrangement made it possible to measure velocity and swirl angle profiles along both the horizontal and vertical diameter. The position 32.3 D downstream of the header corresponds to the location of the orifice meters in the gas metering station. In addition, velocity and swirl angle measurements were made at 3.8 D and 6.8 D from the header, although for meter-run B only.

All traverses were made at least twice and high repeatability in the measurements was experienced.

3.2. Experimental results

Again we will pay attention to meter-run B in the configuration where meter-run C is closed and the other three are all open. The flow behavior in pipe B represents the typical situation for all the meter-runs, so there is really no need to bother with the others. What regards the swirl angle profiles these are relatively uninteresting since there were hardly measured any swirl angles at all. With reference to the previously made discussion of the probability for solid body rotation to occur in the meter-runs, this was as expected. Swirl angle profiles for meter-run B are therefore omitted.

The development of the axial velocity profiles in meter-run B of the scale model is shown in Figure 5. The positions 3.8D, 6.8D and 32.3D from the header were monitored along the horizontal diameter. We observed a strong asymmetry at 3.8D, which already at 6.8D was significantly reduced. At 32.3D the velocity profile was only slightly asymmetric, but still being flatter than the fully developed profile. The deviations from the fully developed profile, using the definition from ISO-5167, are plotted in Figure 6. The fully developed profile was taken in the same flow-rig, using tubes with the same wall-roughness as in the scale model. As can be seen from Figure 6 the deviation is higher than 50 % in the worst part of the 3.8 D traverse. After another 3.0 D, the maximum deviation along the examined horizontal traverse is reduced to approximately 25%. At the location of the orifice plate carrier, 32.3D from the header, the deviation over most of the traverse is below 4%.

3.3. Consequences

Through these scale model experiments we have experienced that in the position of the orifice plate the velocity profile has a maximum deviation from the fully developed profile of approximately 4%. This is below the upper limit allowed for according to the requirements in ISO-5167 regarding velocity profile conditions.

Compared to the simulation results for the high pressure gas metering station, there is a distinct difference between measurements and simulations at the position 6.8 D from the header as well as in the 32.3 D position. In the simulations the asymmetry in the axial profile tends to have a slower decay rate than found in the experiments. It must, however, be added that while the experiments were performed at a Reynolds number of $9 \cdot 10^4$, the high pressure natural gas simulations represented a Reynolds number of $9 \cdot 10^6$. The effect of increasing the Reynolds number is to reduce the decay rate for anomalies like swirl and asymmetries.

Therefore to achieve a proper evaluation of the Tandem simulator also the scale model experiments should be simulated. The results from this action are the topic of the next chapter.

4. THE SCALE MODEL - MEASUREMENTS VS. SIMULATIONS

The Tandem simulator was set up to simulate the flow in the Plexiglas scale model. Main geometrical data and operational properties for the simulations were in agreement with the specifications for the scale model experiments given in the previous chapter. The entire geometry was divided into 5 sub-geometries. The only modification relative to the gas metering station of Figure 2 is that the straight pipe and the S-bend were exchanged with a straight pipe, see also Figure 4. The manifold was operated with meter-runs A, B and D open for flow, while outlet C was closed.

4.1. Tandem simulation of the scale model.

The presented results are restricted to the flow conditions in meter-run B. Cross-sections 3.8D, 6.8D and 32.3D from the header were covered by axial velocity measurements along horizontal traverses. These velocity profiles are plotted together with the corresponding simulated profiles in Figure 7. Deviation between the fully developed simulated profile (k-ε turbulence model) and the various meter-run B profiles are plotted in Figure 8. The results show that:

- Close to the header, in the position 3.8D, the agreement between measurements and simulations is good. The measurements indicate a slightly stronger asymmetry than the simulations in this position.
- 6.8D from the header we observe that both the simulated and the measured profiles are asymmetric, but this characteristic is far more pronounced for the former. This demonstrates that the simulations were not able to reproduce the measured decay rate for the asymmetry between 3.8D and 6.8D.
- In the position 32.3D from the header the simulation predicts a velocity profile still containing a high degree of asymmetry. The measured axial velocities on the other hand, exhibit a profile that is nearly symmetric - but not fully developed. The maximum deviation from the fully developed profile (k-ε turbulence model) was found to be 6.5% according to the simulations (Figure 8) versus typically 4% for the measurements (Figure 6).

4.2. Discussion of the scale model results

Unexpectedly skew axial velocity profiles were found in the position of the orifice plates when simulating the gas metering station using the Tandem/Phoenics simulator.

This fact and the question it raised to the validity of the simulation results put forward the idea of building a Plexiglas scale model of the gas metering station. Measurements on this scale model showed that there were discrepancies between the high Reynolds number natural gas simulation results and the low Reynolds-number scale model measurements.

To examine the Reynolds-number effects, Tandem simulation of the scale model experiments was performed. As the results presented in this chapter illustrates, Tandem/Phoenics does not predict the development of the asymmetry in meter-run B in the metering station with desired accuracy. This is also the case for the scale model. Particularly between the positions 3.8D and 6.8D this is evident.

Reynolds-number effects. It is known that an increase in the Reynolds number tends to decrease the decay rate for swirl and asymmetry in long straight pipes. Through the two sets of geometrically similar simulations we have ascertained that in the position 32.3D into meter-run B the low Reynolds number case deviates from the fully developed profile by a maximum of 6.5% while the corresponding figure for the high Reynolds number case was 10%. The only conclusion we shall draw from this observation is that Reynolds number effects are present and must be considered when the scale model measurements are evaluated.

Wall roughness. All simulations are performed with hydraulically smooth walls. Due to prior experience this is a reasonable choice both for the Plexiglas tubes and for the process pipes in the gas metering station. However, the value used for the wall roughness parameter is itself a model assumption that influences the decay rate. A sensitivity test was therefore made. The main conclusion with respect to the decay rate in the meter-runs remained unchanged even with relatively rough walls. This excludes inappropriate setting of the roughness parameter to be the source of error for the deviation between measurements and simulations.

The turbulence model. Comparison of simulated and measured axial velocity profiles 3.8D from the header showed good agreement. This means that the entrance conditions for the velocity profile in meter-run B is essentially correct. In other words, the manifold geometry seems not to be the source for the disagreement between simulations and measurements. We know from earlier verification tests[1][2] that the Tandem/Phoenics system is able to predict the development of an asymmetric velocity profile, when this is generated by a curved bend. One major difference in the flow conditions downstream of a curved bend relative to that downstream of a sharp-edged tee (which is the equivalence of the gas metering station manifold) is the much higher turbulence intensity associated with the latter.

The performance of the turbulence model is demanding for correct simulation of the decay of swirl and asymmetry in straight pipes. For the simulation of flow in bends, manifolds, tees, etc., the turbulence model is of minor importance for accurate prediction of the mean velocity field since the dominant forces in these geometries are inertia forces (e.g. pressure and centrifugal forces).

On the basis of the above observations and considerations our explanation to why the simulations fail to predict the developing process of the asymmetry downstream of a sharp-edged tee is lack of generality in the applied k-ε turbulence model. One major deficiency with the k-ε model is that it is isotropic. Particularly in 3-D problems of the kind examined here this might prove to be a deteriorating limitation.

5. SIMULATION OF THE SCALE MODEL USING REYNOLDS STRESS TURBULENCE MODEL

5.1. General

The most advanced turbulence model presently available to Phoenics, using curvilinear coordinates, is the k-ε turbulence model, which is the one we have used throughout the reported results.

We knew that the companies behind computer codes as Phoenics, Fluent and Flow-3D were working hard to support their codes with more advanced turbulence models than the k-ε model. Contact was taken with CHAM (Phoenics) and Fluent Europe and they were both requested to perform a simulation of the flow in a T-junction using their most advanced turbulence model. The boundary conditions for the T-junction was made so that the case became similar to the flow in the combined header and meter-run B of the scale model. At the time of completing this paper only Fluent Europe have accomplished the work.

5.2. Results

Simulations with the Fluent code[5] have been performed using both the k-ε turbulence model and the full Reynolds-stress turbulence model. Both models are optional in the latest version of the program. The geometry is described in curvilinear coordinates and the grid density is approximately as in the Tandem set-up.

K-ε turbulence model. Figure 9 shows the axial velocity profiles resulting from the Fluent simulations plotted together with the measured velocity profiles. The Tandem/Phoenics counterpart to these results are found in Figure 7. We can see that the two sets of plots (Fluent versus Phoenics) compare relatively well (notice the difference in y-scale). The most striking difference between the two sets occurs for position 3.8D where the Fluent results deviates considerably more from the measurements in the 'lower end' of the curve than do the Phoenics results. This tendency lasts also for 6.8D. At 32.3D both sets of results have a maximum deviation from the measurements in the radial position 0.8D. Due to the Fluent results the deviation from the fully developed profile reached a maximum of 9% in this area.

The Reynolds stress turbulence model (RSTM). The results from the application of the RSTM of Fluent are plotted together with the measured velocity profiles in Figure 10. We observe that the solution has changed considerably due to the switch-over from the k-ε to the RSTM. Unfortunately the RSTM did not improve the performance of the simulations. On the contrary, both in the positions 3.8D and 32.3D from the header the RSTM results show a significant increase in the deviation from the measurements compared to the k-ε model. In the mid-position, 6.8D from the header, the results compare to the measurements approximately as the k-ε model does. Because of the poor comparison with the experimental data we have found no reason to include profiles showing the deviation from the fully developed profile for the RSTM.

6. CONCLUSIONS

In this paper we have focused on the ability for computational models to predict the decay of asymmetries in axial velocity profiles in long straight pipes. For the design of gas metering stations this is an important parameter since it influences the required upstream straight lengths. Here we have concentrated on the asymmetry in the meter-runs of the gas metering station. From scale model experiments and from computer simulations using two different turbulence models we draw the following conclusions:

- The velocity fields in the meter-runs of the gas metering station is entirely a consequence of the design of the manifold. The twisted S-bend upstream of the manifold has no influence to the flow in the meter-runs. Therefore the metering station can be considered as if laying entirely in the horizontal plane. This eliminates the occurrence of solid body rotation in the meter-runs.

- The sharp edged tees connecting the meter-runs to the header in the gas metering station generate a strongly asymmetric velocity profile in the entrance part of the meter-runs. The asymmetry decays and according to the measurements the profile deviates from the fully developed profile by less than 5% in the position of the orifice plate, 32.3 D from the header. In this position the profile is nearly symmetric, but flatter than the fully developed profile.

- The simulation results based on the k-ε turbulence model was in good agreement with the measurements in position 3.8D. Over the next few diameters, however, relatively large discrepancies occurred. After 32.3D the maximum deviation from the fully developed profile was 6.5 % for the simulations versus approximately 4% for the measurements. The simulations using the k-ε model obviously underestimate the decay rate for asymmetries generated by a sharp-edged tee. It is likely to believe that the cause is lack of generality in the turbulence model.

- Adoption of the advanced Reynolds stress turbulence model (RSTM) to the test geometry proved to give velocity profiles that deviated even more from the measurements than the k-ε results. Effort should be made to try to determine why the RSTM failed to improve the k-ε results.

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3 ISO 5167 (1991). *Measurement of fluid flow by means of orifice plates, nozzles and venturi tubes inserted in circular cross-section conduits running full.* International Standardisation Organisation.

4 Rosten H I and Spalding D B. *The Phoenics equations*. CHAM TR/99 November 1987, program version 1.4.CHAM Ltd, Bakery House, 40 High Street, Wimbledon SW19 5AU, England.

5 *Fluent User's Guide - Version 4.0*. Fluent Inc., Canterra Resource Park, 10 Cavendish CT., Lebanon, NH 03766, USA

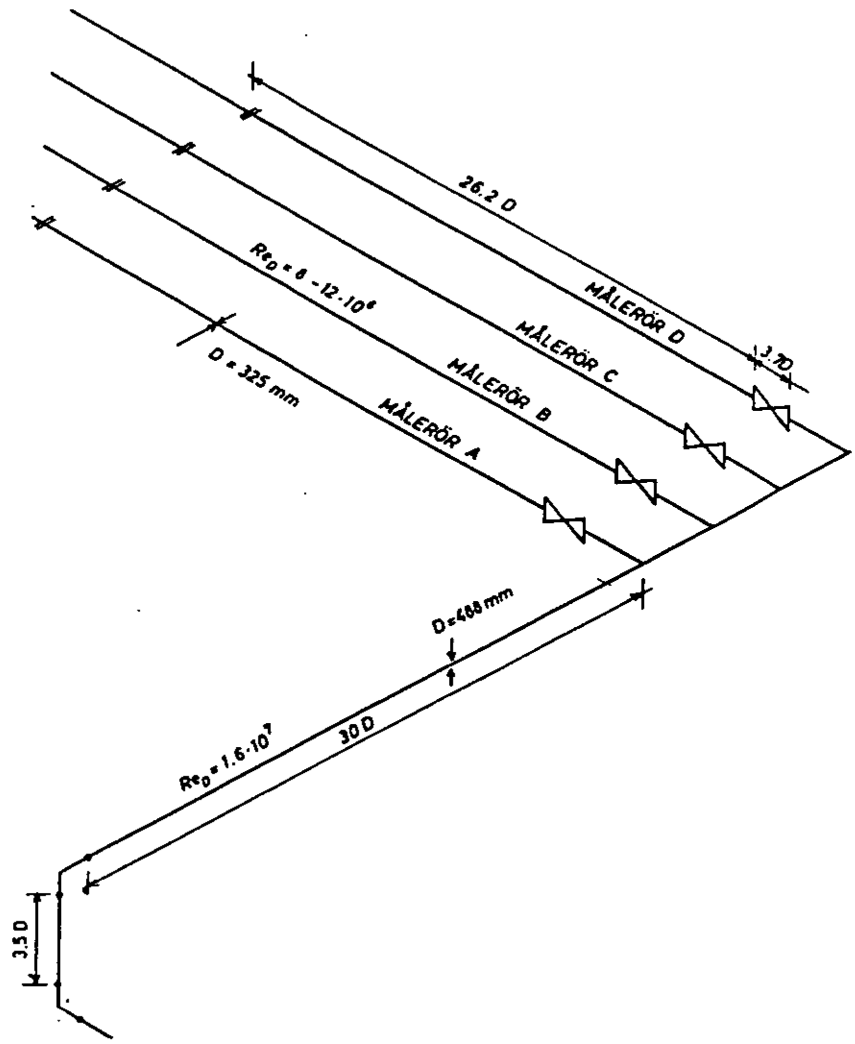

Figure 1. Outline of the Gas Metering Station

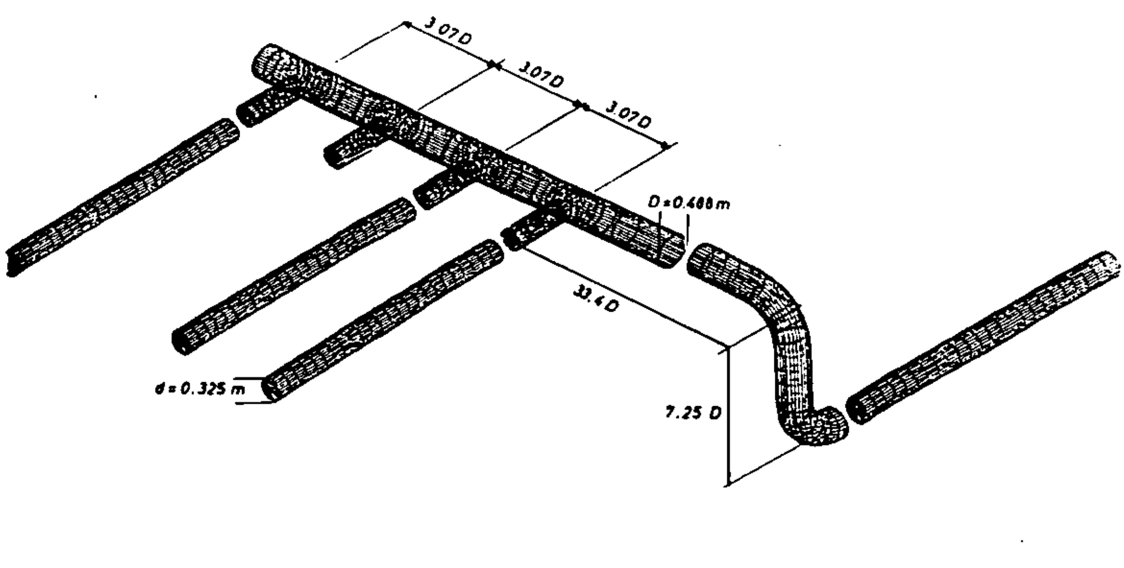

Figure 2. The gas metering station interpreted for Tandem

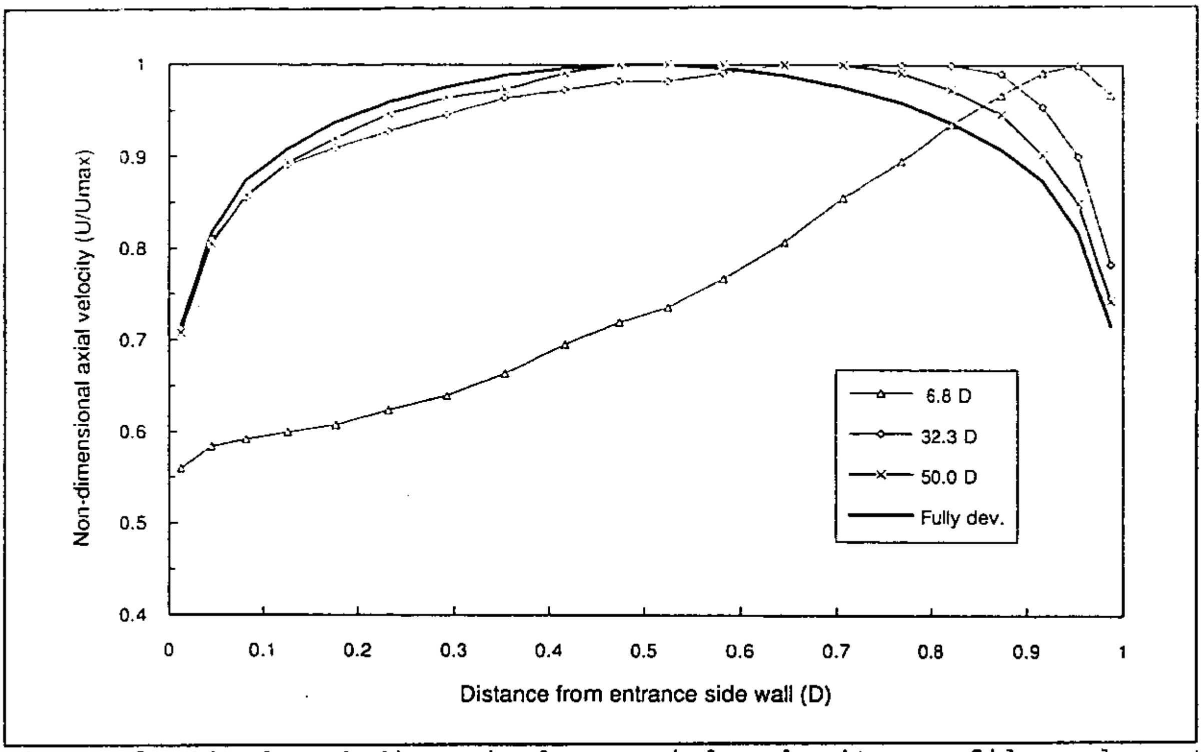

Figure 3. Simulated dimensionless axial velocity profiles along the horizontal diameter in three positions in meter-run B of the gas metering station.

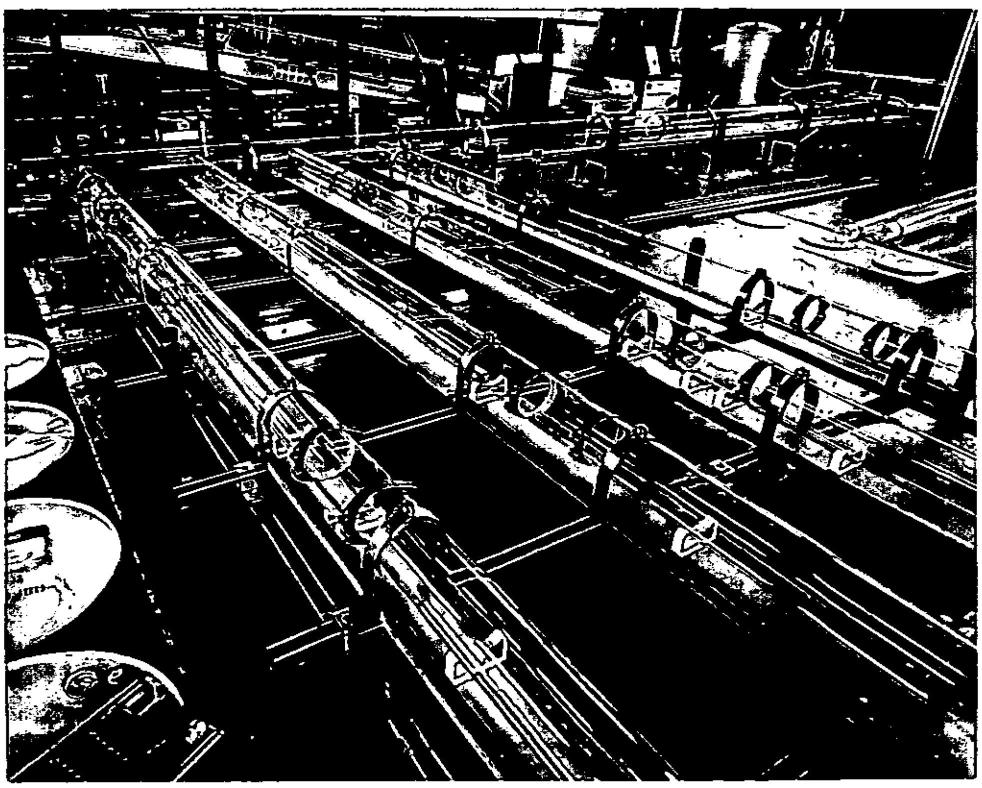

Figure 4. Photography showing the header and the meter-runs of the scale model

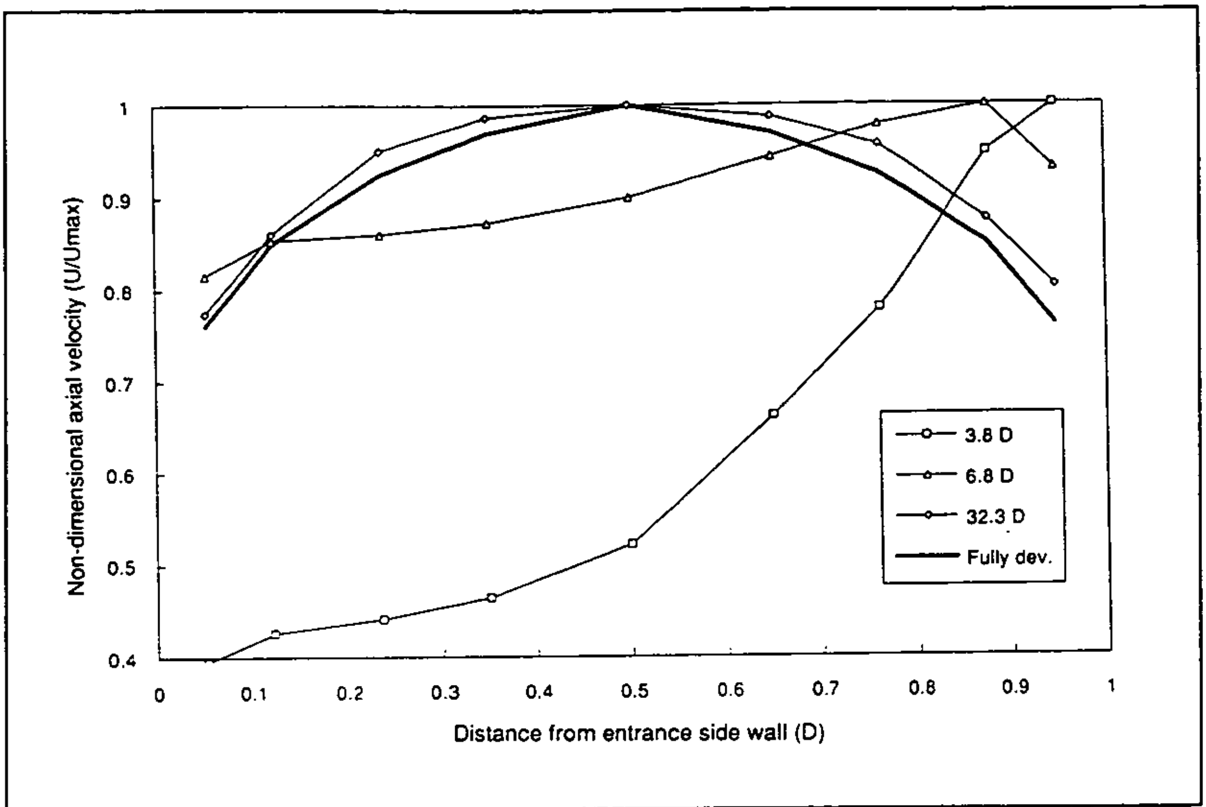

Figure 5. Velocity profiles horizontally traversed measured 3.8D, 6.8D and 32.3D downstream of the header in meter-run B of the scale model.

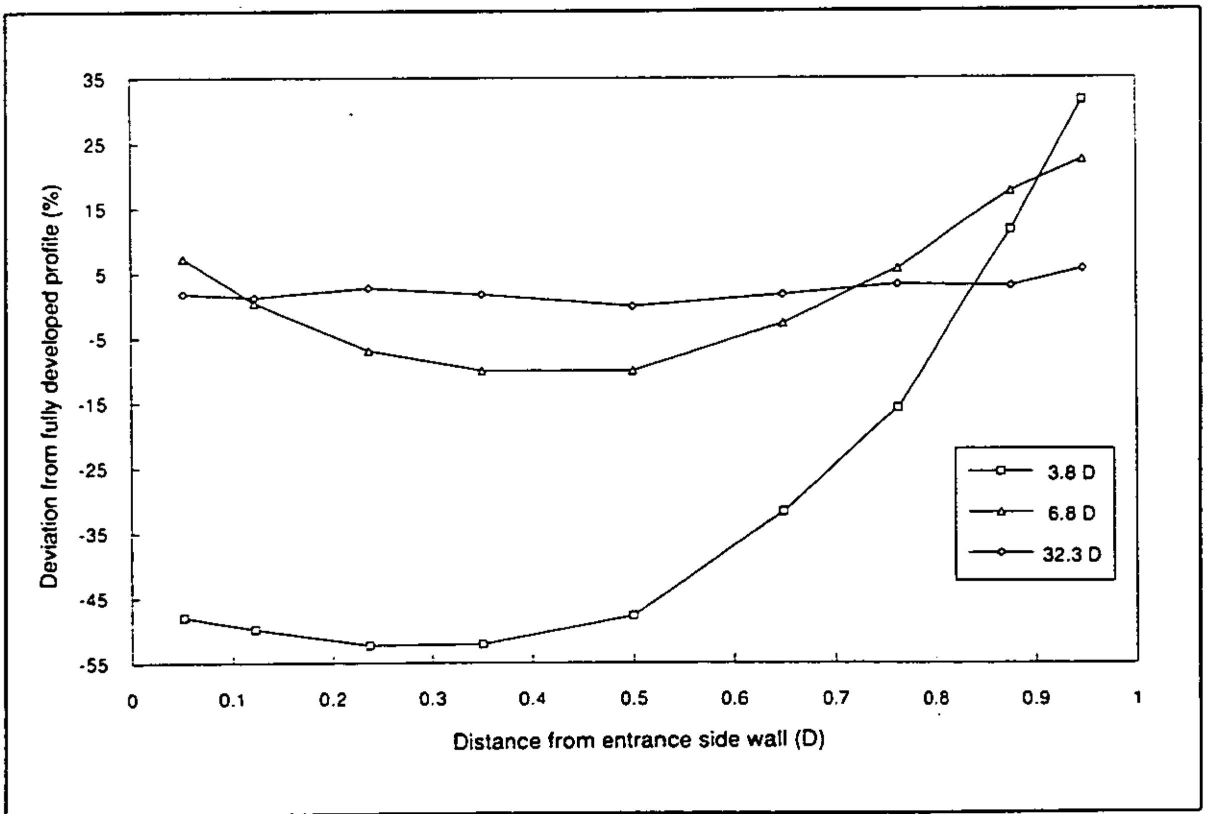

Figure 6. Deviations from the fully developed velocity profile for the profiles measured in the three highlighted cross-sections of meter-run B in the scale model.

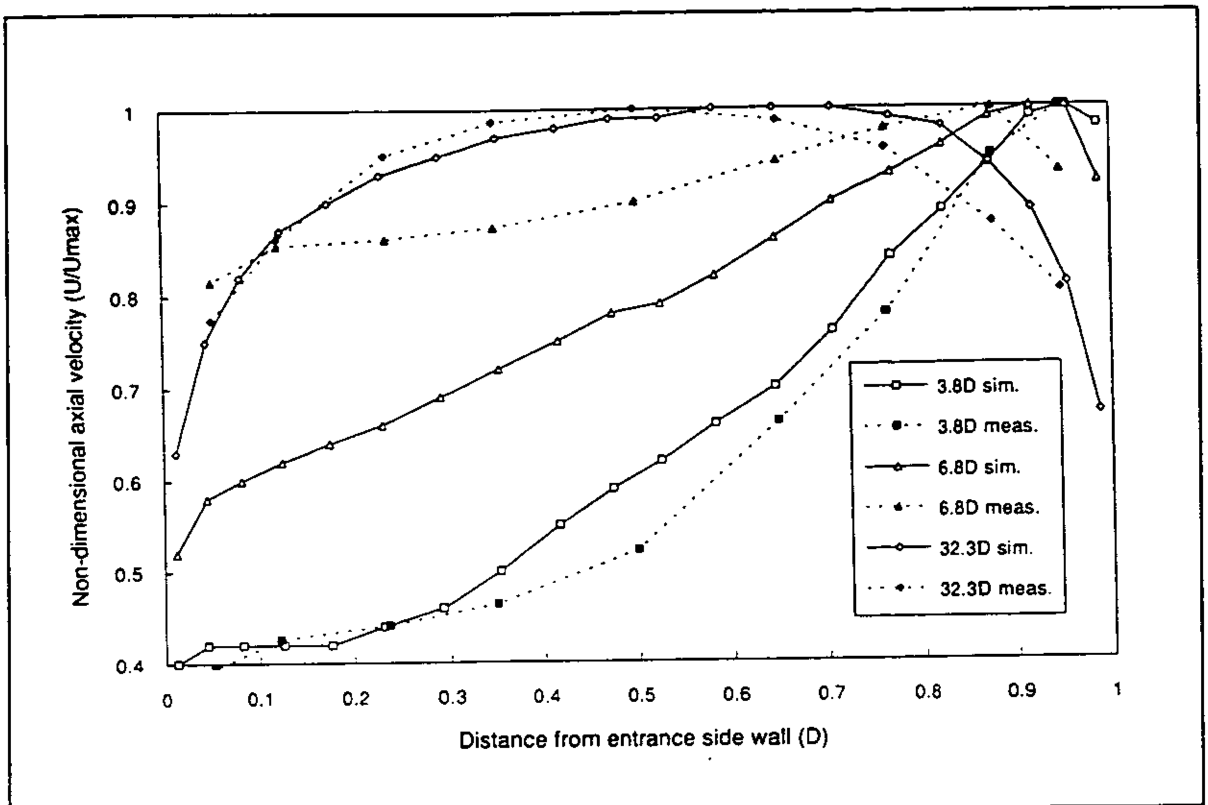

Figure 7. Comparison of simulated and measured axial velocity profiles in the positions 3.8D, 6.8D and 32.3D into meter-run B of the scale model.

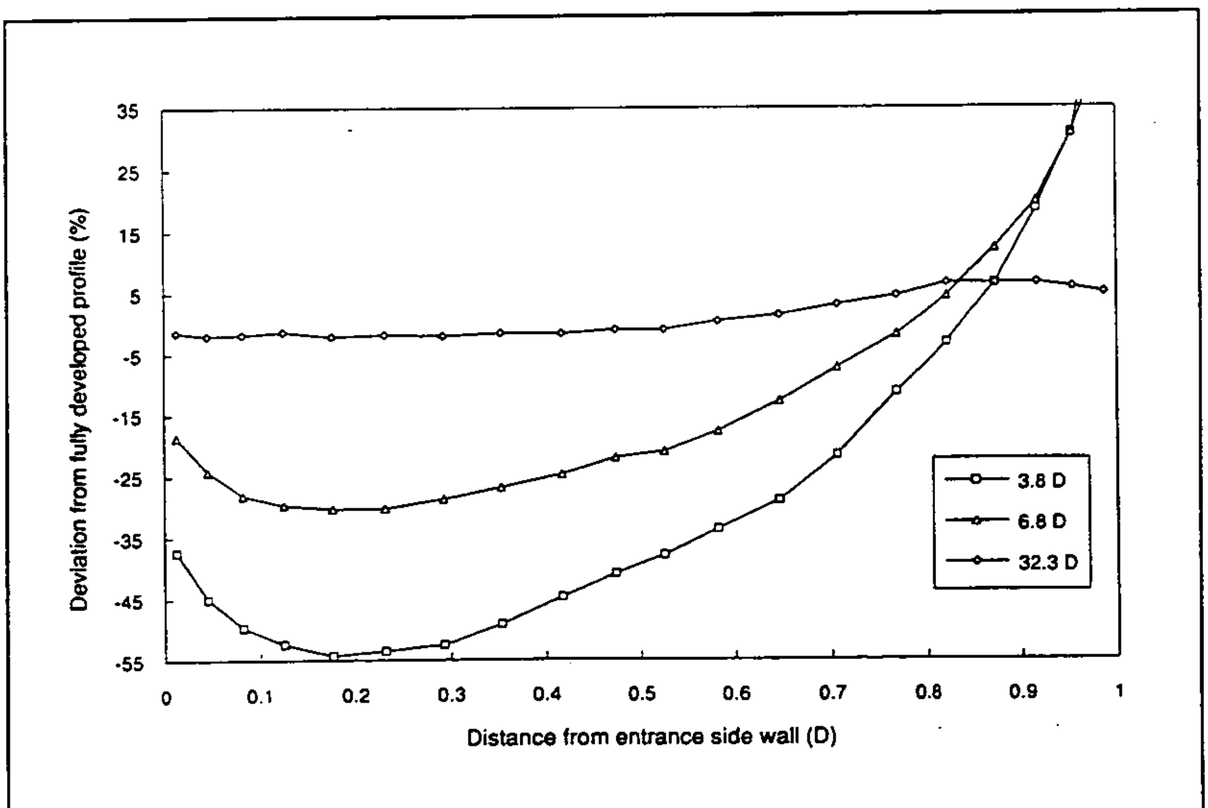

Figure 8. Simulated deviation from fully developed profile for the three highlighted cross-sections of meter-run B in the scale model.

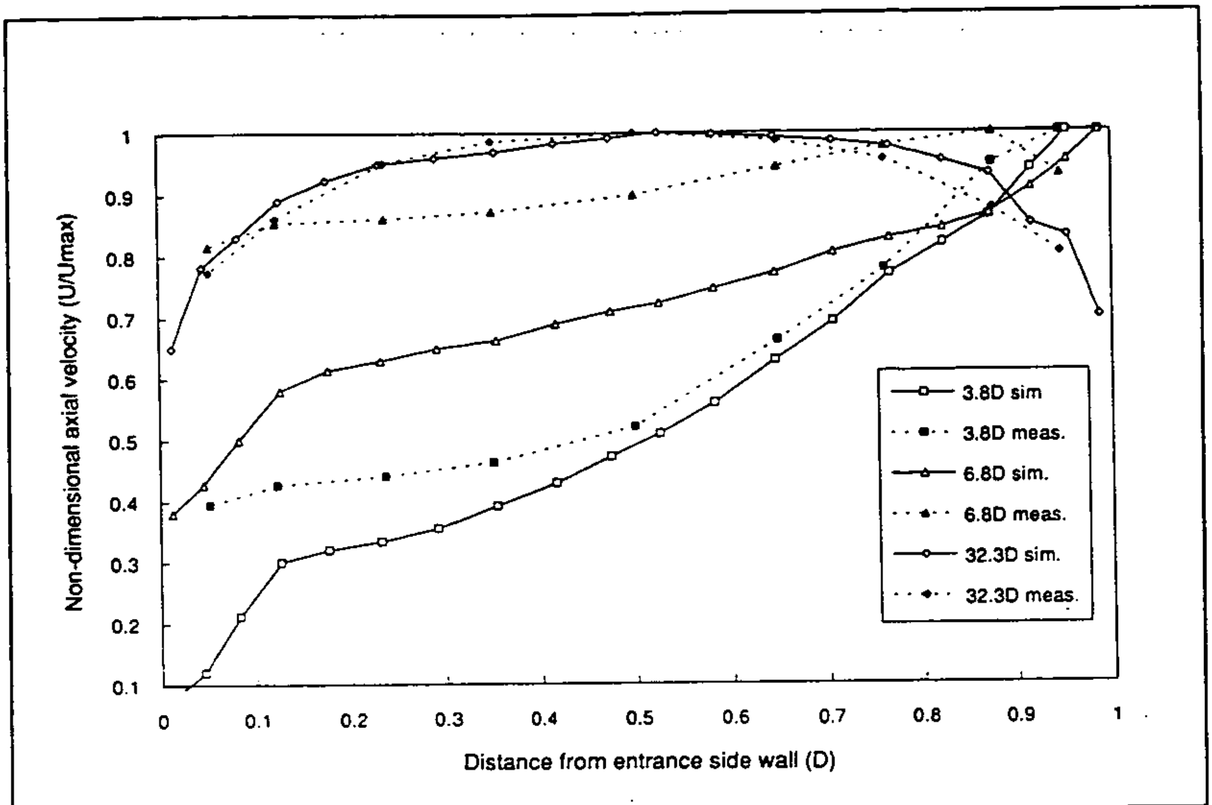

Figure 9. Comparison of velocity profiles found from T-junction simulation using Fluent with k-e model and from measurements in the scale model.

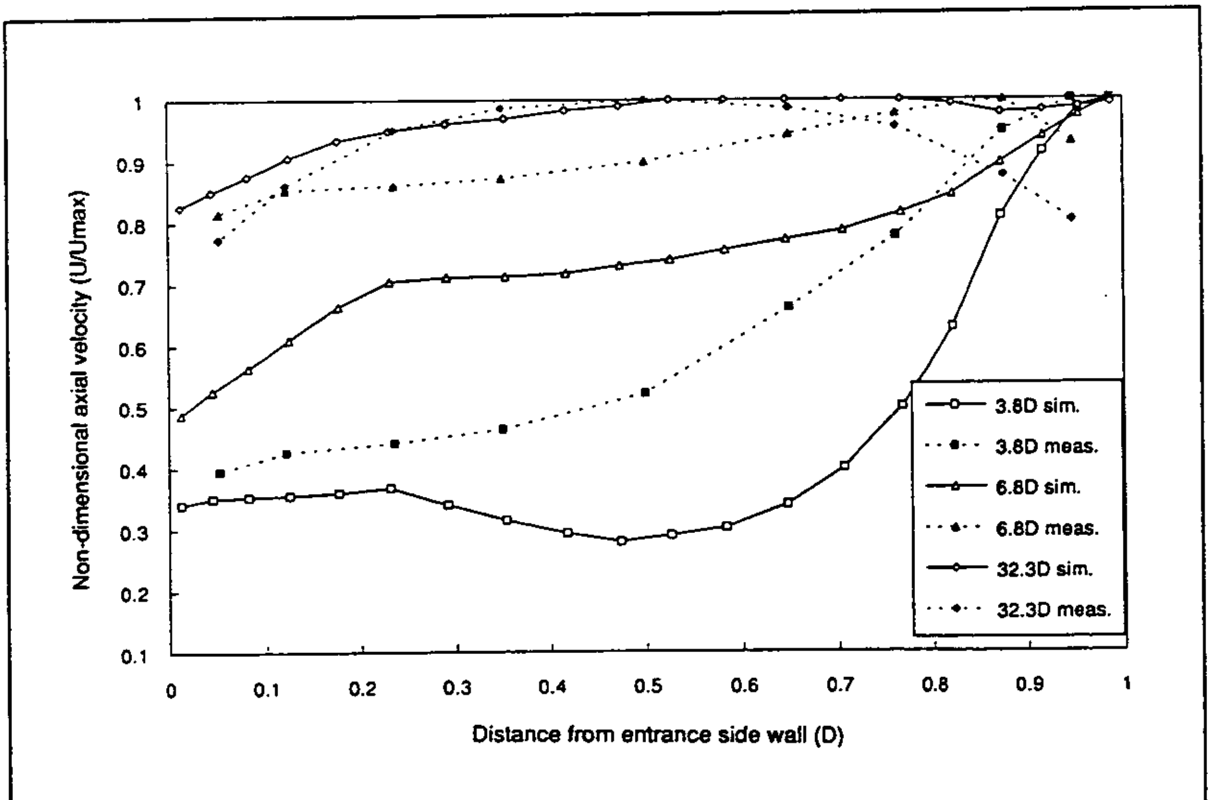

Figure 10. Comparison of velocity profiles found from T-junction simulation using Fluent with RSTM and from measurements in the scale model.