The Long Pipe at CICLoPE

Outcome of Discussions at Forli'-Stockholm-Lausanne-Kingston; March-October 2004

By

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Summary:

The following outlines a three to four year plan for the development of a high Reynolds number, long pipe facility for detailed turbulence measurements in combination with computational efforts to provide a focus of activity for leading international researchers in the field of wall-bounded turbulent flows. The facility is intended for at least ten years of basic research and has the potential for extensions with more direct impact on applications, such as the study of the effect of non-smooth walls or non-isothermal conditions, the evolution of various non-equilibrium flows, and of flows with some particulates. The designated location at the tunnels at the "Ex Industrie Caproni" site in Predappio, Italy, in coordination with the Universita' di Bologna at Forli', with its two large tunnels, can also be the potential location of other unique fluid dynamic facilities, such as a special setup for the study of two and three dimensional separated flows at high Reynolds numbers.

To accommodate the proposed long pipe experiment, at least 1,000 m^2 of the "Caproni" tunnels would have to be renovated, with the remaining parts at least secured and cleaned. We estimate the cost of such renovation to be in the order of one million Euros. A more accurate estimate for such renovation should be accessible by the representatives of the University of Bologna. A similarly rough estimate, based on our experience with several major aerodynamic facilities currently located in Chicago, Lausanne, Princeton and Stockholm, yields an additional one million Euros for the construction of the long-pipe facility. We recommend that various experimental participants in our international consortium are engaged early in the planning stages towards the third major element of the plan to acquire, adapt and develop the measurement and diagnostic instrumentation. By securing funds from various agencies in their respective countries, and subsequently designing, developing and testing the various modules of diagnostic instrumentation in their own laboratories, the major experimental participants in the consortium will actively contribute to this most important third part of the plan. We strongly believe that this approach would provide two important benefits:

> 1) The "distributed" initial financing of the diagnostic instrumentation and computing facilities, with a total cost estimated at one and a half to two million Euros and
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> 2) Ensure the availability of the instrumentation necessary for the accurate determination of the flow field as soon as the facility is completed.

The infrastructure costs would include at least one permanent technician, a contract with a security company (e.g. for guards), and annual funds of 100 k€ for maintenance. An additional

two-hundred thousand Euros may be required per year for the support of the scientific team working to acquire the data base of measurements from the long pipe. This support as well as that required for the processing and analysis of the data base would be readily available from the international participants in the wall-bounded flows consortium through the agencies of their respective countries. However, a coordinated effort should be made by the group to secure funds from international agencies such as the soon to be established “European Science Foundation.”

Background:

Although the equations governing turbulent flow of fluids are well known we are, in the words of Richard Feynman (The Feynman Lectures on Physics, 1964), still not able to understand its *qualitative* content. "Today we (still) cannot see that the water flow equations contain such things as the barber pole structure of turbulence that one sees between rotating cylinders." In other words, understanding the overwhelming richness of flow phenomena, especially in *high Reynolds number turbulent* flows, remains one of the grand challenges of physics and engineering. High Reynolds number turbulence is ubiquitous in aerospace engineering, ground transportation systems, flow machinery, energy production (from gas turbines to wind and water turbines), as well as in nature: e.g. the absorption processes for ‘green-house gases’ in the oceans where the diffusive transport depends on the complex interaction of turbulent eddies with the salinity and temperature-related density stratification. Similar dynamics are also of importance in atmospheric turbulence in conjunction with the spreading of pollutants.

The understanding of turbulence dynamics in general have taken a giant leap with the explosion of computing power in the high-end of high-performance computing, but even with the worlds largest computer the Reynolds numbers attainable are moderate in direct numerical simulations of turbulent flows, and will not reach the higher values of practical interest for decades to come. Hence the fundamental understanding of the physics of high Reynolds number turbulence must be gained from experiment. Of particular interest are the issues concerning the degree of universality of the high Reynolds number turbulence dynamics. Such an improved understanding would directly and significantly increase the reliability of advanced simulation tools for the virtual engineering of transportation systems and flow machinery, and have a far reaching impact on areas such as combustion, atmospheric dispersion and weather prediction.

So why choose a pipe flow to gain the desired understanding of high Reynolds number turbulence. The reason is that most flows of industrial interest are bounded by solid walls on which so-called boundary layers form. Since turbulence is generally produced within these boundary layers, they often control the rest of the flow, and intuition will not be effective without the full understanding of the wall-bounded regions and the interplay between pressure gradient, transition and separation. The fully developed turbulent pipe flow has been chosen because the other two canonical wall-bounded flows - fully developed plane turbulent channel flow and the zero-pressure-gradient turbulent boundary layer - present additional "uninteresting" experimental difficulties.

A key element of the dynamics of wall-bounded turbulent flows is the interaction of the near-wall, inner region, with the large turbulent scales of the outer region. These two distinct regions are present in all wall-bounded flows and are coupled through the overlap region. The velocity profile in this region appears to exhibit a large degree of universality between different flows and can with be described by a logarithmic function (to a certain degree of accuracy). The inverse of the slope of this profile in a semi-logarithmic plot is usually referred to as the Kármán constant and is denoted by κ. Recently, the Kármán κ constant has received attention of a mixed kind, which some may consider of just academic nature. While it had seemed safely confined to the range 0.40 to 0.41 for many years, recent extensive experimental efforts have given values as different as 0.436 and 0.38. This impacts extrapolations to high Reynolds numbers commonly used in many applications; a difference of 0.025 in κ changes the skin friction at $Re_x = 10^8$ by 2%, and therefore the predication of the drag of an airplane by 1%. This is significant in terms of guarantees in the airline industry. Also, an uncertainty in a presumed universal constant by ± 5% is of major impact on the various turbulence models and the coefficients used in them.

Interactions amongst several members of our group over the last few years motivated us to meet for a two-day workshop at Princeton University in October of 2003. As researchers in the field of turbulence, with a recent focus on high Reynolds number flows, we have not been satisfied with the rate of progress in this technologically important field of fluid dynamics. For example, we recognize that while wall-bounded flows present a wonderful array of problems in turbulence, there are still controversies and uncertainties over fundamental issues. Therefore, we have been motivated by the idea of gathering world-leading scientists in the field of turbulence research for a closely coordinated collaborative effort to make fundamental breakthroughs in the fundamental issues of high Reynolds number turbulence.

The series of workshops that are organized are intended to maximize discussion and introspection with an atmosphere that encourages an open mind approach to the issues. During the workshops, enough time is planned for each of us to convince others of what is right at the present level of understanding in the spirit of true intellectual inquiry. We hope that out of these meetings will emerge a shared sense of understanding, and perhaps with a clearer sense of where our future efforts should lie.

Several recent experiments on zero pressure-gradient turbulent boundary layers (in USA, Sweden, The Netherlands and Australia) have yielded ground-breaking results and have substantially modified the consensus about the so called log-layer constants. The values of these constants or parameters are vital in drag predictions for airplanes and in many other engineering flow applications. Recent experiments at relatively high Reynolds numbers in a plane turbulent channel flow (in Germany and USA) have also shown interesting similarities and differences as compared to the boundary layer case. It appears as the log-layer constants in this flow are very close to those recently determined in the boundary layer case. Experiments just completed in the USA with high Reynolds number boundary layers under various pressure gradients, which in some cases lead to non-equilibrium conditions, have emphasized the importance of the independent measurement of the wall shear stress.

It is now clear that the only wall-bounded flow that may not require such measurements is the *fully developed* pipe flow, where the careful measurement of pressure gradient can lead to an accurate determination of the friction velocity. This is one of the key factors in selecting the long pipe configuration for the ***C****enter for* ***I****nternational* ***C****ooperation in* ***Lo****ng* ***P****ipe* ***E****xperiments* (CICLoPE). High Reynolds number experiments have recently been carried out for this case in the USA. The facility is located at Princeton University and is known as the "superpipe." These experiments have attracted much attention both from a purely scientific viewpoint and from the viewpoint of potential importance for engineering applications. The results exhibit a number of interesting similarities with the other canonical cases, but also some distinct differences.

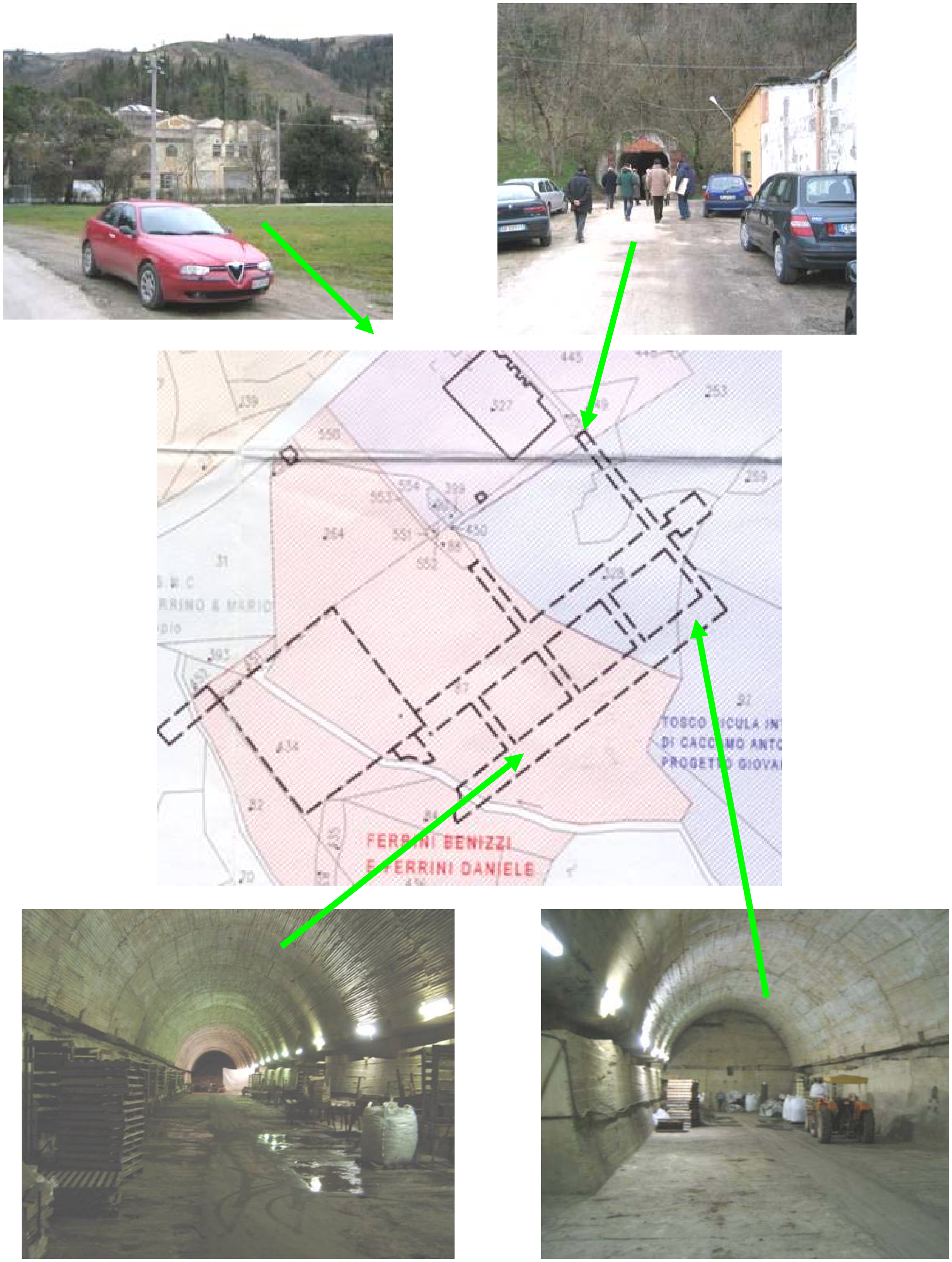
In the boundary layer and channel flow cases, conventional experimental facilities have been used, which readily allow a number of different well tested experimental flow measurement techniques. In the superpipe experiments a high pressure (of about 200 atmospheres) is used to achieve the high Reynolds numbers. This has been successfully implemented and measurements of mean velocity have been made with Pitot tubes. Hot-wire measurements have also been used to obtain information on spectral density and fluctuation intensities. The recent findings for the three canonical flows have triggered a series of highly interesting research issues about universality of turbulence features in different regions of the flow near surfaces, in particular the so called overlap region. Of primary interest to the scientific and engineering community is to complement the pipe flow experiments from the superpipe facility with new measurements at high Reynolds numbers in a facility that would readily allow detailed flow structure measurements, and high resolution turbulent-fluctuations measurements.

New computations with moderately high Reynolds number direct numerical simulations (from Spain, USA and Japan), have also suggested a role of the inner/outer layer interaction in wall-bounded flows that has not yet been fully understood or not mapped out in detail. Well-planed high Reynolds number experiments can also play a crucial role here. In addition, the understanding of the differences in the character of the outer layer between the three canonical flows is as yet incomplete and would require new high Reynolds number experiments to be significantly advanced. While the prospects over the next few decades for direct numerical simulations to be accessible even for the scientific community are not good, detailed comparisons between even the available results with carefully carried out measurements in the flow field of a fully developed pipe can be of significant impact on our understanding. In addition, accurately measured mean velocity and turbulent intensity profiles in the proposed “Long Pipe at CICLoPE” can be a most desirable data base for the theoretical analysis of turbulent flows with asymptotic methods. Many of the recently developed models of turbulence can be positively impacted by an extensive data set from this unique facility complimented by an extensive array of diagnostic instrumentation. For example, detailed measurements of the Reynolds stresses and two point correlations of the components of fluctuating velocities can provide a most needed data base. Only a facility like this large diameter long pipe can be used with modern instrumentation such as Micro Particle Image Velocimetry (MPIV) to document these quantities at high Reynolds numbers.

Ingredients of Required Support:

1. Preparation of the Caproni Tunnels
2. Construction of Long Pipe Facility
3. Acquisition of Instrumentation and Computing Equipment
4. Support for Scientists

This white paper will be circulated among other participants in the forthcoming meeting: “Second International Workshop on Wall-Bounded Turbulent Flows”, The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, November 2-5, 2004; *Organizers: Hassan M. Nagib, Alexander J. Smits, and Katepalli R. Sreenivasan.* The first workshop was hosted by Professor Lex Smits at Princeton University on October 16 and 17, 2003, and the group agreed to gather for a second meeting in approximately one year.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1. The Scientific Case for CICLoPE:

The scientific issues that can be addressed with a long, high Reynolds number pipe facility are many and concern fundamental issues regarding the asymptotics at high Reynolds number and their universality between different canonical flow cases. This understanding is crucial for the accurate prediction of flows in many technological circumstances as well as in geophysical and environmental situations. The general aspects discussed above illustrate the great need today to bridge the growing understanding of turbulent flows at low to moderate Reynolds numbers with the situation at high Reynolds numbers occurring in key areas of industrial interest, in climate modeling etc. The rapid growth of understanding of turbulence at moderate Reynolds numbers has emerged from new direct numerical simulations and recent advancements in experimental techniques. To illustrate the situation we can give the example that the largest direct numerical simulation of turbulent channel flow carried out so far is for a friction Reynolds number of 1,160 whereas we here aim for friction Reynolds numbers of more than 10,000.

The understanding of turbulence at high Reynolds number is of high interest for basic understanding and modeling for CFD-purposes, but also for the design of control techniques that can be effective in practical circumstances. Here, the relative roles of outer and inner layer dynamics are critical elements for the possibility of generating the future generations of methods for turbulence control. Some of these aspects are now addressed at the highest possible DNS Reynolds numbers. The added value of the presently proposed type of experiments should be very high for these efforts.

Many different types of scaling issues can be addressed with a high Reynolds number facility as the proposed CICLOPE, where the crucial aspect is the possibility of detailed measurements of turbulence quantities in the different regions of the flow. Given the choice of a fully developed pipe flow configuration within the space of the "Caproni" tunnels, the desired Reynolds number, coupled with the limitation on the usable maximum velocity and the available measurement techniques for detailed turbulence measurements, leads to approximate upper and lower bounds for the physical dimensions of the pipe.

a) The Reynolds number: The requirements for a high Reynolds number pipe flow facility have been analyzed and the primary parameter is the maximum achievable Reynolds number. The magnitude of the Reynolds number determines the turbulence scale separation and thereby the size (in terms of wall units, i.e. the smallest scales) of the overlap region, which is of primary interest in the study of universality issues. A suitable aim has been judged to be about $2\text{x}10^6$ based on centerline velocity and pipe diameter. This would give an overlap region with a size that is of the order of 10^4 in terms of wall units, and the pipe radius would correspond to about $4\text{x}10^4$ wall units; i.e., $Re_\tau \sim 40{,}000$ (approximately one tenth of the highest value reached in the superpipe experiment but more than an order of magnitude larger than any other previous fully developed flow experiment.)

b) The maximum velocity: In order to avoid any compressibility effects and to optimize the conditions for the measurement techniques planned for the experiments the maximum velocity is planned to be 50 m/s.

c) The pipe diameter: The above choices give a pipe diameter of 0.60m (using air at room temperature and ambient pressure as the flow medium). For the further design studies three alternatives will be kept open, viz. 0.50m, 0.60m and 0.70m.

d) The pipe length: The available length of the tunnel in Predappio is now about 110m although further excavation may extend this length. At present this could give a pipe length of up to 90m. For the three choices mentioned above this would give an L/D of 180, 150 and 129, respectively. All of these could probably be considered satisfactory. However, an L/D of 150 (corresponding to the 0.6-m pipe diameter) could be large enough to provide the desired spatial resolution and accessibility, and would provide the long development length for not only the mean flow but also the turbulence and its higher order statistics. The 0.6-m diameter would probably be sufficient to allow a person to transport on a skid with rollers along sections of the pipe for inspection, minor adjustments and occasional cleaning.

e) The motor power: The motor power is determined by the power factor of the circuit, the cross sectional area of the pipe and the maximum velocity. A first very rough estimate of the power factor yielded an estimate of about 2.0. This is for natural reasons much higher than for typical wind-tunnels, mainly because of the length of the pipe. At the maximum velocity this would give the following three approximate requirements for the motor power with the three options for the pipe diameter: 30 kW, 42kW and 58kW, respectively.

f) Fan requirements: The high pressure drop in the circuit is not suitable for a standard single stage axial fan, but should be possible to accommodate with a two-stage axial fan. This option is presently studied. In connection with the fan one should make sure to install sufficient noise absorption in the parts surrounding the fan, and possibly in the corner vanes.

g) Pipe requirements: The critical component in the circuit is the pipe. It has to satisfy stringent requirements for straightness, smoothness and circularity. These are difficult requirements to fulfill and will mean that a substantial part of the total cost will be that for the pipe itself. The tolerance level for the roughness is presently under study. At least in the latter part of the pipe the roughness should be less than one viscous unit (and perhaps even substantially less than that). At 50 m/s the former requirement translates to a tolerance for roughness of about 0.01 mm.

h) Cooling: The circuit has to be equipped with a heat exchanger with a cooling power that is at least the same as the power of the motor. Probably, it is quite easy to incorporate an additional 60 to 75 kW cooling capacity into the cooling and ventilation system for the renovated “Caproni tunnels.”

i) Dual pipe: A possibility that has been discussed and should be further studied is that of having a second pipe of significantly smaller diameter (say a fourth of that of the primary pipe) mounted on the same structure as the big pipe. This would allow a convenient Reynolds number variation etc at a moderate extra cost.

2. Technical Specifications for CICLoPE

2.1. Laboratory layout

The long pipe will be installed inside the area of the second tunnel of the Predappio site (see figure 2.1). The first 30 meters of the tunnel will be completely restored and adapted to host the measurement laboratory of CICLoPE. The rest of the tunnel will be only cleaned and prepared for the systems installations. The pipe will be positioned beside the tunnel wall and concrete foundations will be built to fix the different elements of the circuit to the ground. The driving unit will be in the far end of the tunnel outside the measurement laboratory. A special concrete base will be made for the driving unit installation on the ground.

In the main corridor, office rooms for researchers, a small kitchen and other service facilities will be hosted.

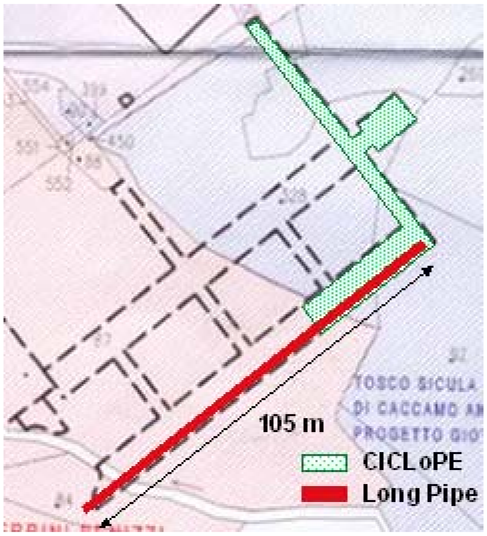


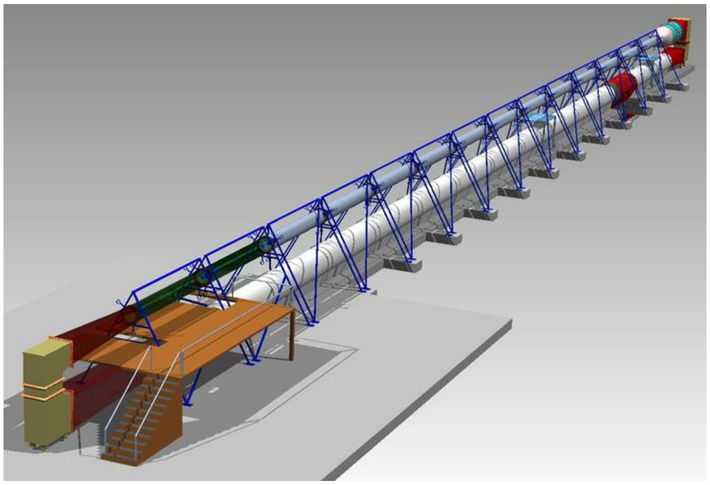
Figure 2.1. Layout of laboratory and pipe location at the Predappio site.

2.2. The apparatus

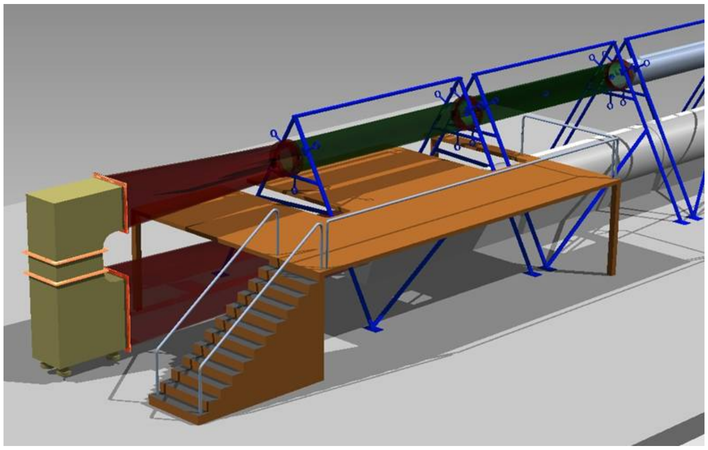
The pipe will be part of a closed-circuit apparatus, which will provide better control of the flow conditions in the pipe itself and inside the laboratory avoiding the presence of moving air. Moreover, it will reduce the power needed to keep the required velocity in the test section. The tunnel layout resembles an ordinary wind tunnel, however the main difference is the long test section which is also gives much higher friction losses than in the test section of a wind tunnel. However many of the various aerodynamic components are the same as in a wind tunnel (corners, diffusers, screens, contraction etc.) and for several of these components we have used the recent experience gained when constructing the MTL and BL-wind tunnels at KTH Mechanics, Stockholm.

The apparatus will be mounted in a vertical position, i.e. with the return section below the measurement pipe. This decreases the space required and keeps tunnel space free for future new experimental set-ups. The pipe will be positioned in the upper part of the circuit. A platform will be mounted to reach the test section. Along the pipe different cart moving on rails will be positioned in order to easily access all parts of the pipe for inspection and maintenance (see figure 2.2).

To achieve good flow homogeneity at the pipe inlet a settling chamber will be mounted with the possibility to insert honeycomb and a series of screens. To reduce the length of the diffusers and allow as much length as possible to the pipe, expanding corners will be used.



(a)



(b)

Figure 2.2. (a) Overall schematic of the apparatus. The position of the fan and the number of elements is tentative. (b) Detailed view of the test area – Also shown is the test section (green), the diffusers (red) and the expanding corners (gray).

a) The pipe: The pipe will have a diameter of 600 mm and will be (at a minimum) 84 meters long. This value corresponds to a length over diameter ratio (L/D) of 140 which provides enough length to establish a fully developed flow. The diameter is large enough to give the possibility to access the inside of the pipe in order to inspect, clean and to make small adjustments. However the tunnel will be further excavated in order to investigate the possibility to host an even longer pipe.

The pipe will be made of a series of pipe elements which will be joined together. Each element is mounted in a frame made of iron bars which will be fixed to the concrete basement (figure 2.3). The joint between the elements will be designed and manufactured carefully in order to guarantee the alignment of the pipe. Moreover, each element should be possibly removed in order to have access inside the pipe for cleaning and inspections. The length of each element depends on the material used. Two possibilities concerning the pipe material have been studied. Aluminum allows pieces of pipe to be obtained at relatively low cost. However, the maximum length of each piece is in that case limited to 3 meters. Each piece must be also treated “a posteriori” to reach the requested geometric tolerances.

The cost of the material (joints excluded) for this solution is approximately 20 k€. A second possibility is molded carbon fiber reinforced plastic pipe elements. In this case very long pieces can be directly obtained using standard procedures. However, both transportation problems and the dimensions of the laboratory limit the length to 13 meters. The quality of the inner surface depends only on the quality of the mold, therefore good roughness surfaces can be obtained.

In any case, the relatively large diameter and the Reynolds number attained limit the value of the roughness parameter k_{rms}. The obtained values can be reached by means of standard manufacturing procedures.

The cost of the molded pipe elements is much more expensive (about 450 k€).

The test section will be fixed at the end of the pipe. Different test sections will be designed and built depending on the measurements techniques which will be used. The test section used for hot wire measurements will allow for the mounting of a calibration unit inside the test section in order to allow calibration of hot wire probes “in situ”.

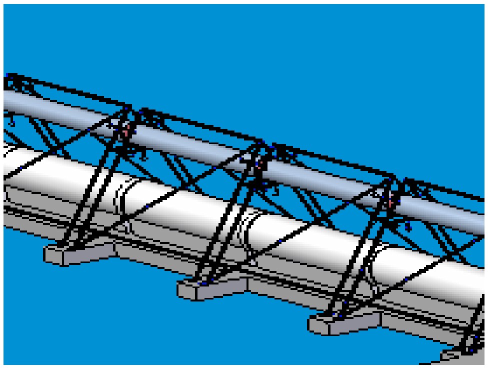


Figure 2.3. Schematic view of 2 joined elements of the circuit– See the frames fixed to the ground, the pipe, the concrete elements for the return part and the rails for the inspection carts

b) Corners and diffusers: Diffusers are used in order to slow down the flow before the corners and to transform the pipe section from circular to rectangular to join the corners. To limit the length of the diffusers, some expansion will be made through expanding corners, similar to those employed successfully in the BL tunnel at KTH. In the last corner, just before the settling chamber, where the Reynolds number is at a minimum and flow separations may occur, the vanes will be individually adjustable. The geometry and the spacing of the vanes will be studied to avoid shedding or separation phenomena. Corners can be made of wood while the diffusers could be built in fiber-glass

c) Return section: The return pipe is made by standard concrete elements which are produced for water sewage systems. Each element is 2 meters long and about 6000 kg heavy. Inside a perforated cylinder (1.4 m in diameter) will be mounted and rock wool will be positioned in between for sound absorption. Different point of access for inspection and cleaning will be created. An estimated cost for this part is approximately 15 k€.

d) Driving unit: The driving unit will be located in the return circuit outside the main laboratory. In figure 2.4 a possible configuration is shown. Inside the fan, a cylindrical body will be mounted filled with noise absorption material. The nose of the central body will be shaped as half of an ellipsoid while the end will be shaped as a cut-off cone to limit and fix the flow separation. A 60 kW motor will be mounted axially just behind the fan and will be cooled from air coming from an external cooling pipe system interfaced with the ventilation of the tunnel. Due to the moderate loads, in order to provide the necessary pressure jump, a two-stage axial fan is needed. The fans diameter will be 1.4 m with a hub diameter of 0.6 m. Each fan will have 8 blades which may be chosen to be automatically adjustable. The driving unit will be mounted on special silent block to minimize the vibrations transmission to the ground.

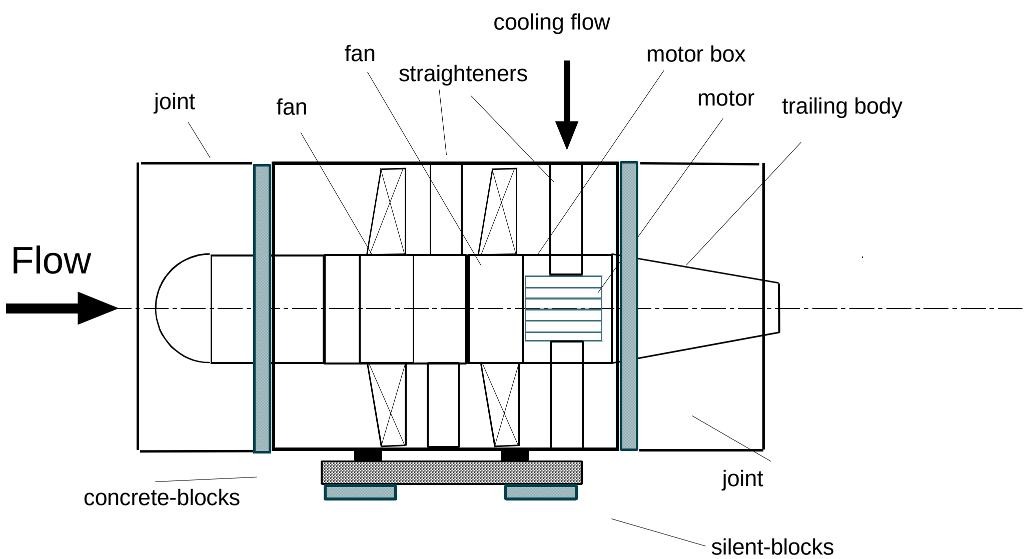


Figure 2.4. Schematic of the driving unit

e) Cooling system: A stable temperature in the section will be provided by a cooling circuit, which will be designed to be interfaced with the cooling and ventilation system of the tunnel. The heat exchanger will be mounted in the circuit before the fan. In this position the cross section area is large which will minimize pressure losses across the heat exchanger. Moreover, the position far away from the test section and the presence of the fan will even out any spatial non homogeneity in the temperature distribution. A control system will be designed to provide a stability of the flow of 0.1 °C.

f) Stagnation chamber and contraction: The stagnation chamber will have a diameter of 1.7 m giving a contraction ratio CR=8 (see figure 2.5 for a layout of the pipe inlet section). The stagnation chamber will be equipped with one honeycomb and three screens in order to reduce lateral components of the flow and to improve the homogeneity over the cross section at the pipe inlet. Parameters of the screens and the honeycomb have been chosen following those used in the BL-tunnel at KTH. Honeycomb and screens will be mounted in order to be easily extracted for cleaning and inspection.

The shape of the contraction will be the same as the one used at the MTL and BL wind tunnels at KTH Mechanics. The shape was obtained by means of inviscid/boundary layer calculations optimizing the pressure distribution in the contraction walls to avoid separations of the flow.
The end of the contraction will be shaped in order to host inserts like honeycomb or grids that can be mounted to speed up the turbulence development process.

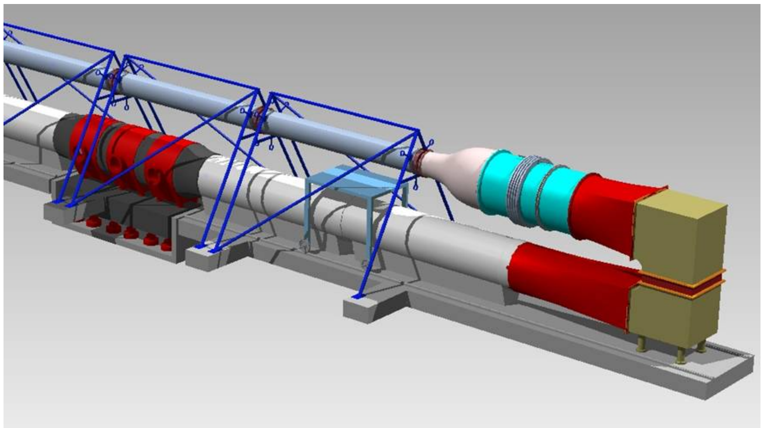


Figure 2.5. Schematic view of the pipe inlet – stagnation chamber (blue), contraction (white).

g) Pressure losses: A detailed estimation of the pressure losses has been performed. The final loss coefficient for the proposed geometry at 50 m/s is λ=1.91. In this preliminary estimate, the pressure losses at the heat exchanger have not been considered. The total pressure jump is approximately 3000 Pa for a total power required of 40 kW. In the figure below the different loss coefficient for the elements of the circuit are shown in figure 2.6. Note that the pipe is responsible for the 75% of the total losses.

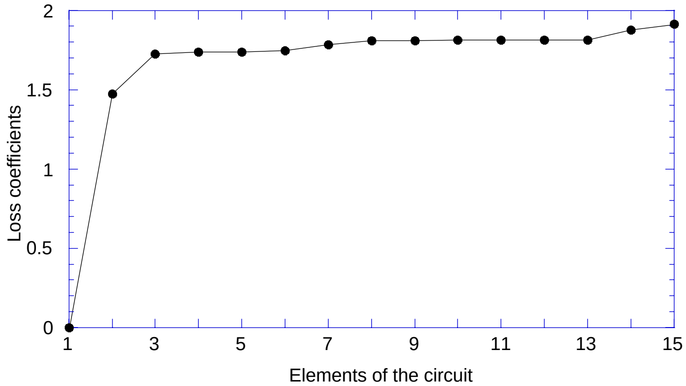


Figure 2.6. Total pressure loss coefficient for each element of the circuit

3. Instrumentation and Computing Equipment for the Long Pipe

The instrumentation requirements for this project are particularly important in that the accuracy and completeness of the data will be the project's most important aspect. To ensure quality, it will be essential to have complementary means for measuring mean and turbulence quantities. It is therefore suggested that the facility be equipped with (1) hot-wire anemometry systems capable of measuring multiple velocity components and some spatial correlations (perhaps as many as 30 channels); (2) a three-component LDV system; and (3) a dual plane stereo PIV system. In addition, a multiple channel, high-accuracy pressure measurement system will be required to record static and dynamic pressure data.

3.1. Pressure measurements

High specification differential pressure transducers with an assortment of ranges will be needed in order to accurately resolve dynamic pressures and pressure gradients over the full Reynolds number range. Computer-controlled multi-port scanning equipment such as that provided by Scanivalve will permit rapid acquisition of multiple pressure readings. In addition, a high-accuracy absolute pressure transducer or barometer will be required to measure the ambient pressure.

A distributed network of thermocouples along the pipe monitored by the acquisition computer and perhaps linked directly to the cooling system will permit accurate temperature control in the facility. Temperature and ambient pressure measurements together permit accurate determination of fluid density.

The pipe needs to be instrumented with wall static pressure tapings along its entire length (perhaps every 4 diameters). In addition, to measure the pressure gradient in the pipe and hence the wall shear-stress, a large number (at least 20) static pressure tapings will be needed along a section of the pipe in the fully developed region of the flow, and upstream of the primary measurement station (it needs to be upstream so that probes inserted into the flow at the measurement station do not interfere with a simultaneous measurement of the pressure gradient).

To measure circumferential variations, up to 20 static pressure tapings and Preston probes need to be positioned circumferentially at one location downstream of the measurement station.

3.2. Traversing Systems

For physical probe measurements (hot-wires and Pitot probes, a high spatial resolution traversing systems will be required. The accuracy is achieved by use of fine pitch traverses on which both Pitot and hot-wire probes can be easily mounted (such as those offered by Velmex) in combination with a small stepper motor or DC motor with optical encoder. The traverse needs to be mounted on a removable insert that fits precisely into the pipe wall. Additional inserts need to be available for other purposes, including static pressure comparisons, Preston probe mounts, and experiments that are yet to be devised.

3.3. Hot-wire anemometry

Hot-wires will be used to obtain accurate turbulent velocity signatures with high frequency response. Up to 30 (?) anemometer channels will be needed (for example, AA-labs) allowing for racks of hot-wires to be used. The calibration facility will be fully automated under computer control. A typical design of a calibration tunnel is shown in figure 1.

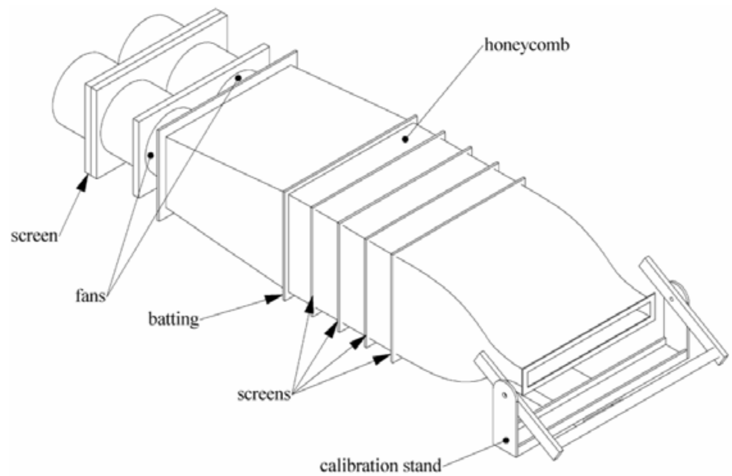


Figure 3.1. Sketch of a typical hot-wire calibration wind tunnel (after Kunkel 2003). The hot-wires are mounted on a stepper-motor driven calibration stand allowing automated calibration of multiple hot-wires simultaneously.

The hot-wire signals will be sampled using a high-speed multi-channel data acquisition system (see below).

3.4. Laser-Doppler Velocimetry

A system capable of measuring three components of velocity is required, mounted on a 3-D traverse. Suitable systems are available from Dantec or TSI. Specification should call for the smallest possible measurement volume.

3.5. Particle Image Velocimetry

A dual plane stereo PIV system will be needed. The system will take advantage of the latest advances in high speed digital imaging and high-speed laser technology. In addition, long-distance microscope lenses will be required to enable measurements at small scales. The system will need to be very flexible to allow for many measurement configurations. One such arrangement is shown schematically in Figure 2, where stereoscopic PIV velocity fields are measured simultaneously for a small field of view, recording the small scale motions, and a large field of view recording the large scale motions. The long distance microscopes enable one camera pair to view a small field at the working distance out-side of the large pipe.

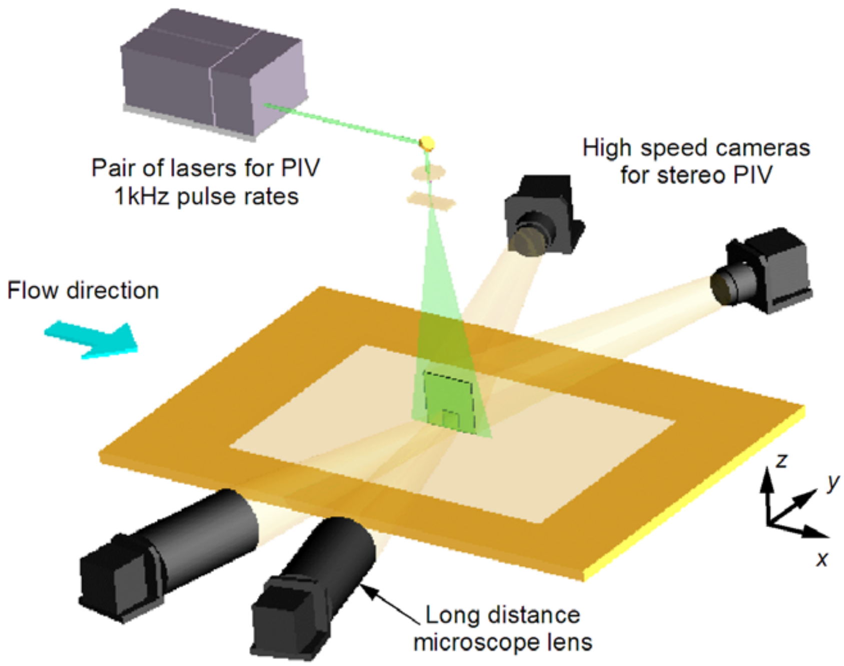


Figure 3.2. Dual plane stereo-PIV set-up.

3.6. Computing Facilities

Two facility-specific personal computers equipped with high- and low-speed data acquisition cards, DVD/CD-RW and suitable software will be used for both data acquisition and on-site processing. Multiple internet connections will be needed.