

Construction and Instrumentation of a Closed Loop Facility for PIV Measurements Inside Rib-roughened Pipes

I. Lorenzo Mercado^{1*} and S. Ruck¹

1: Thermal and Fluid Dynamics System Design, Karlsruhe Institute of Technology, Germany

* Correspondent author: isaac.mercado@kit.edu

Keywords: Pipes, Surface-structures, Closed loop, Turbulent flow, Refractive index

ABSTRACT

Efficient thermal control is critical for maintaining the reliability, performance and operational longevity of high-temperature engineering systems. Rib turbulators acting as turbulence promoters disturbing the thermal and hydrodynamic boundary layers have played a significant role in heat engineering and highly thermally loaded applications. Heat transfer enhancement and flow field turbulence produced by attached or detached ribs applied as surface-structures in array or single configurations inside rectangular ducts have been extensively studied. Less research however has been conducted for rib-roughened circular cross-sectional channels, where CFD simulations lack experimental work. Therefore, a new facility is being constructed at the Institute of Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT). The facility is a closed loop with the purpose of studying the turbulent flow field in a rib-roughened circular test section capable of operating in a Reynolds number (based on the test section's inner diameter D and the bulk velocity u_B) range of $5000 \leq Re \leq 50000$, and for understanding the effects of varying rib geometrical parameters on the turbulent mixing, secondary flow field and velocity gradients. The test section is a 4.23 m long pipe with a section made out of polypropylene and transparent borosilicate glass to allow for Particle Image Velocimetry (PIV) velocity measurements, where the method of Refractive Index Matching has been applied to overcome the optical aberration caused by the curvature of the test section's glass wall.

1. Introduction

Rib-roughened surfaces enhance convective heat transfer, reduce fluid–solid interface temperatures and material thermal gradients, and thereby can improve thermal efficiency, component lifetime, and load flexibility. While many studies have examined Reynolds number and rib-geometry effects in ribbed square or rectangular ducts [Tropea et al. (2007), Labbé (2013), Fang et al. (2015), Castro et al. (2021), Ruck and Arbeiter (2021)], experimental data for internally structured circular channels remain scarce and detailed turbulence transport analyses are largely limited to CFD. LES studies by Abdel-Wahab and Tafti (2004) focused on rotational effects such

as Coriolis forces and buoyancy effects and demonstrated that curvature strengthens one side of vortex pairs, leading to asymmetric turbulence distributions. More recently, Kang and Yang (2016) and Kang and Yang (2017) conducted LES inside a structured pipe with square ribs to analyze the effects of different rib-pitch-to-rib-height ratios on the heat transfer. They identified that regions with high heat transfer enhancement are due to the higher turbulent kinetic energy and correlated temperature fluctuations to velocity-component fluctuations. There is however limited experimental validation and most research has consisted on structured tubes under a constant surface heat flux condition for analysing dimensionless number correlations, with no insight into the three-dimensional flow field and into the turbulent and advective flow processes from which enhanced convective heat transfer derives. Since the effects of geometry-induced secondary flow cannot be transferred from rectangular to circular cross-sectional pipes as flow structures differ fundamentally in their formation and spatial development, a new refractive-index-matched closed loop facility is been developed at the Institute of Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT) in order to conduct three-component experimental measurements to obtain u , v and w velocity fields and to understand the influence of the pipe's curvature-driven secondary flow dynamics. The surface curvature on both the inside and outside of the wall are responsible for optical aberration and laser beam refraction [Zhang (2004)]. The optical distortion increases with increasing wall thickness and curvature, resulting in complicated optical alignment and focal shifts; reduced image clarity and astigmatism; and deformation of the laser beam waist and distortion of the measurement volume. These optical errors can be minimized when the refractive index of the fluid is matched to that of the test sections wall, a technique known as Refractive Index Matching [Budwig (1994), Wright et al. (2017)].

This paper details the test section structure, flow conditioning, pumping and thermal management. Velocity fields will be measured using a stereoscopic Particle Image Velocimetry (PIV) system; the mass flow rate, pressure, and temperature are monitored with calibrated instrumentation; and a LabVIEW-based control and data acquisition system provides closed-loop operation.

2. Design and construction

A 2D diagram of the complete closed loop facility is shown in Fig. 1. The facility is approximately 7 m long, 1.8 m high and 0.63 m³ in capacity. The round test section comprises a 4.23 m long pipe with a polypropylene (PP) and borosilicate (DURAN) glass segment and operates over a Reynolds number range of $5000 \leq Re \leq 50000$. The main components of the facility are:

1. Reservoir tank
2. Upstream tank
3. Settling chamber
4. Contraction zone
5. Test section
6. Optical container
7. Downstream tank
8. Centrifugal pump
9. Coriolis mass flow meter
10. Sump tank

In addition to the main equipment, the facility also incorporates six ball valves to redirect the flow and fill/drain the main loop, three air valves to allow ventilation and reduce air bubble concentration inside the test section, a strainer valve to filter out contaminants, two spring-loaded safety valves to avoid over pressurization inside the facility, four sensors to measure the temperature and pressure during operation, three rubber expansion joints to mitigate vibrations in the pipeline, one submersible pump which operates during drainage, leakage containment walls, a Bosch profile structure framework for support, steel depots for secure storage of the operating fluid, and a National Instruments system for data acquisition.

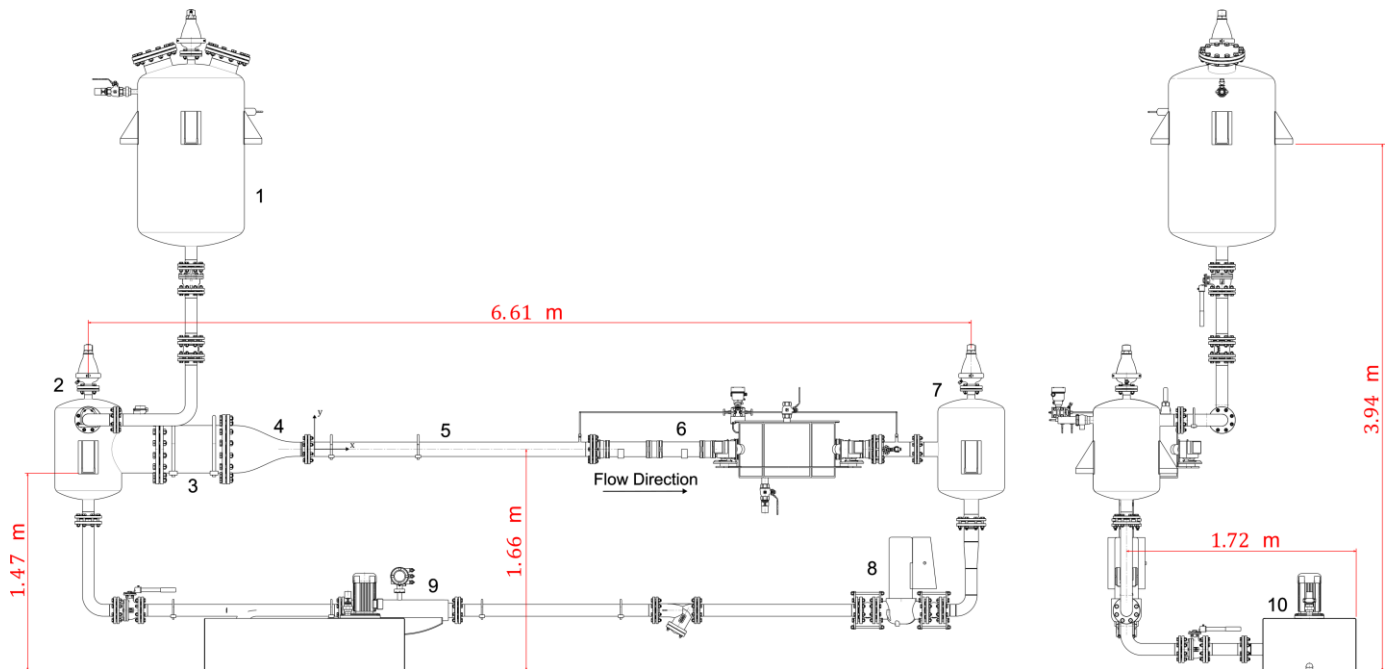


Figure. 1 Side (left image) and front (right image) 2D diagrams of the closed loop facility.

2.1. Test section

Optical aberrations from the glass pipe curvature are mitigated by matching the refractive index of the glass wall ($n_{\text{glass}} \approx 1.473$) via a low viscosity paraffin oil (45.4 %) and ethyl benzoate (54.6 %) mixture (w/w ratio), enabling high-fidelity laser diagnostics. The mixture has a density of $\rho_{\text{mix}} = 917.3 \text{ kg/m}^3$, a viscosity of $\mu_{\text{mix}} = 0.0035 \text{ Pa}\cdot\text{s}$ and a refractive index of $n_{\text{mix}} \approx 1.472$ at a temperature of 293.15 K. Besides the refractive index (which was also calculated experimentally with an AR4 Abbe refractometer), the density and viscosity have only been approximated theoretically.

A 3D view of the complete test section is depicted in Fig. 2. The test section has an inner diameter of $D = 0.1 \text{ m}$. It contains an entrance stainless-steel pipe (part (a)) with a total length of 2.03 m and a pressure sensor type PMC21 installed through a shutoff PN40 angle seat valve, suitable for relative pressure measurements in the range between $1 \cdot 10^5$ to $40 \cdot 10^5 \text{ Pa}$ and with an uncertainty of 0.3 %. For pressure measurements in liquids, the sensor must be installed at the same height as the tapping point, perpendicular to both x and y axes. A 2 m long transparent pipe (part (b)) made out of PP and DURAN glass constitutes the second part of the test section, where the inner walls will be structured by single or multiple arrays of transverse attached ribs.

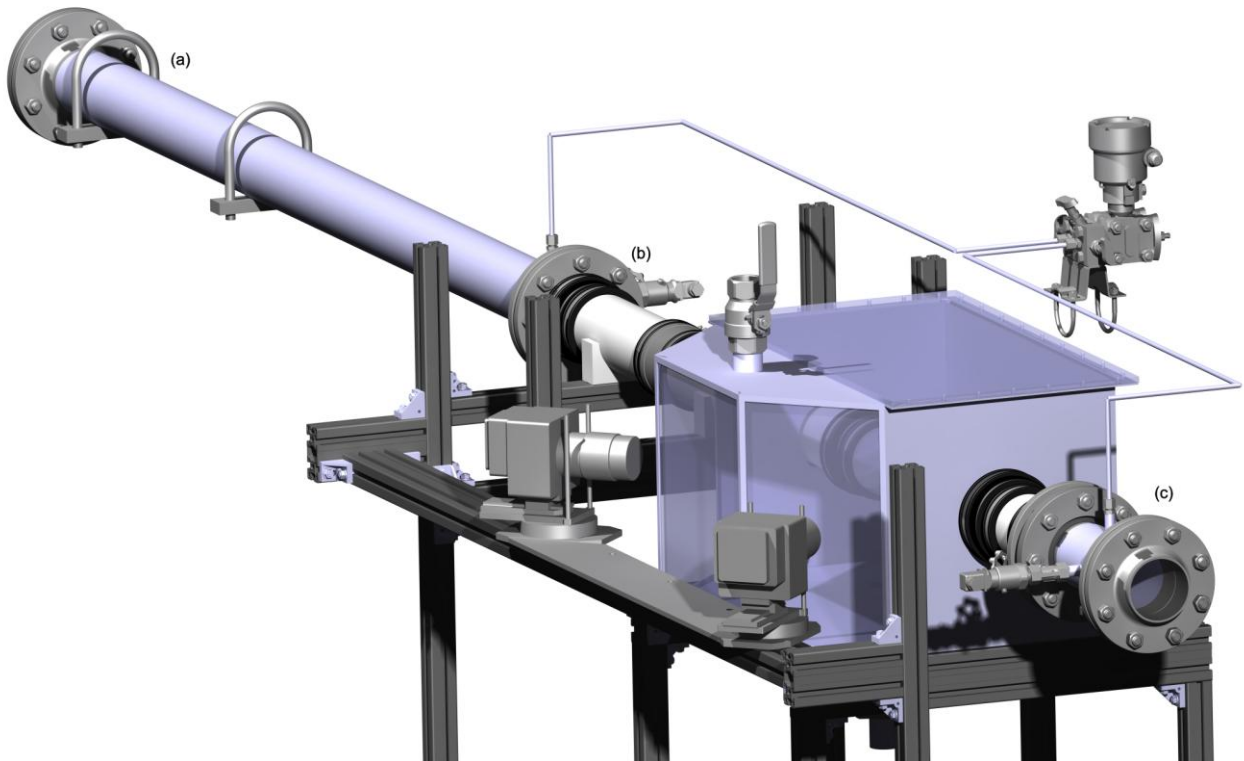


Figure. 2 Isometric view of the test section with: (a) entrance stainless-steel pipe and (b) structured transparent pipe.

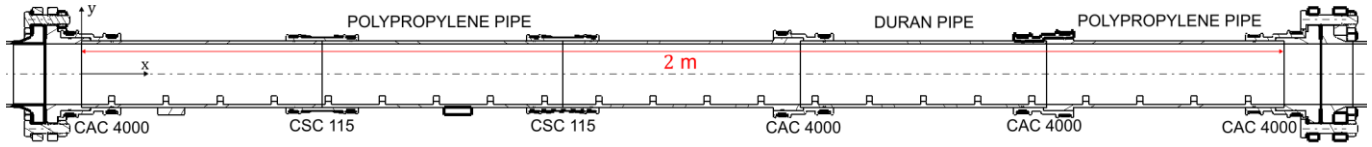


Figure. 3 Sectional view of the PP and DURAN pipe segments.

Glass is very susceptible to cracks and fractures from vibrations and misalignments due to its brittleness. Hence, to minimize damages, the DURAN pipe is connected between two polypropylene pipe segments through two coupling adapters CAC 4000 made out of FKM rated for 110-125 mm and 100-115 mm sizes and for pressure-tightness of $0.6 \cdot 10^5$ Pa. Given the challenges of polypropylene-metal joining and the requirement for an interchangeable rib-roughened test section (in order to study different rib geometrical parameters such as different rib cross-sectional shape or varying rib-height-to-pipe-diameter ratio and rib-pitch), custom flanges with a 110 mm inner bore were fabricated and connected to the PP pipe segments using again CAC 4000 coupling adapters rated for 110-125 mm and 100-115 mm sizes. The structure of the PP and DURAN pipes, including the piping connections between metal-polypropylene and polypropylene-glass, are shown in Fig. 3.

The transparent pipe section is surrounded by a rectangular optical container made out of stainless-steel and with three DURAN glass windows. The container has dimensions of $1.7 \times 0.42 \times 0.40$ m and it will be filled with the oil-ester mixture. The metal plates at the front and back of the optical container have holes for the transparent pipe to run through and will be sealed by using a second pair of CAC 4000 FKM adapters, now rated for 121-136 mm and 100-121 mm pipe sizes. A second stainless-steel pipe with a length of 0.2 m is installed downstream, where a second PMC21 pressure sensor is mounted through a PN40 angle seat valve in order to measure the absolute pressure, again with an uncertainty of 0.3 %. Velocity field measurements and topological analysis will be carried out by seeding the fluid with hollow glass spheres (refractive index of $n_{hs} = 1.52$, density of $\rho_{hs} = 1100$ kg/m³ and diameter of 10 μ m) and by using a Dantec Dynamics time-resolved 3D stereoscopic high-speed PIV system with 12-bit CMOS highspeed cameras and a DM2-527-30 dual head Nd:YLF high speed laser with a wavelength of 527 nm, pulse energy of 60 mJ at 1 kHz and an average power of 90 W at 3 kHz. Errors from the tracer particles should be negligible since the slip velocity and Stokes number take a value of $u_s = 1.74 \cdot 10^{-6}$ m/s and $St = 1.25 \cdot 10^{-5}$ for a Reynolds number of 50000. Additionally, in order to measure the pressure drop caused by the roughness elements, a differential pressure sensor of the type Deltabar PMD75B is connected at the inlet and outlet of the inner-structured pipe through NPT1/4-

18 self-sealing tapered pipe threads. The differential pressure sensor is manufactured out of stainless-steel 316L with FKM seals.

2.2. Contraction and settling chamber

The contraction speeds up the flow, decreases turbulence intensity and creates a uniform flow while avoiding separation zones. As the inlet diameter of the test section is known, an inlet-to-outlet area ratio of approximately 14:1 was applied to the contraction and its curvature was dimensioned with the following 5th order polynomial

$$y_c = y_{CI} - (y_{CI} - y_{CO}) \cdot \left[6 \cdot \left(x_c / L_c \right)^5 - 15 \cdot \left(x_c / L_c \right)^4 + 10 \cdot \left(x_c / L_c \right)^3 \right] \quad (1)$$

where x_c is the distance downstream of the contraction inlet, y_c is the radial distance from the centerline, $y_{CI} = 0.1748$ m is the radial distance from centerline at the inlet of the contraction, $y_{CO} = 0.05$ m is the radial distance from centerline at the outlet of the contraction and $L_c = 0.5$ m is the length of the contraction. There are many types of settling units in order to add uniformity to the flow and break large-scale structures, such as honeycombs, turbulence screens, tube bundles or different perforated plates. The considered settling unit in the facility was a perforated straightener plate dimensioned after Laws and Quazzane (1995) and manufactured out of polypropylene. The perforated plate has a total length of $L_p = 0.123 \cdot D_{SC}$, where $D_{SC} = 0.349$ m is the inner diameter of the settling chamber. First, a borehole with a diameter of $0.1924 \cdot D_{SC}$ is located in the center of the arrangement. Seven boreholes with a diameter of $0.1693 \cdot D_{SC}$ are distributed over a radius of $0.2308 \cdot D_{SC}$. The thirteen boreholes on the outermost circle have a diameter of $0.1462 \cdot D_{SC}$ over a radius of $0.4218 \cdot D_{SC}$. The settling chamber has as total length of $L_{SC} = 0.82$ m and accommodates three perforated plates, each spaced 0.2 m from each other.

2.3. Containers and piping system

Three main tank containers will be used at the closed loop facility: an upstream, a downstream and a reservoir tank. The upstream and downstream tanks are used to reduce velocity and pressure fluctuations as well as swirl effects due to pipe bends. The upstream tank also allows for an appropriate piping connection to the settling chamber and contraction inlet without the need for a diffuser, while the downstream tank serves too as a pressure reference point, reducing the possible occurrence of cavitation. The reservoir tank will be used as a storage unit during

maintenance/inactive periods. All tanks are being manufactured with a wall thickness of 0.005 m, capable of withstanding pressures of up to $11 \cdot 10^5$ Pa. The upstream and downstream tanks have an inner diameter of 0.49 m and a height of approximately 0.75 m, with a capacity of 0.13 m³, whereas the reservoir tank has an inner diameter of 0.79 m and a height of approximately 1.36 m, with a capacity of 0.63 m³. Each tank has an air relief valve of the type D-021 which allows for automatic air admission and release. The valves are installed on top of each tank to reduce the content of air inside the test section and the pump, and to facilitate the filling and draining of the installation. All wetted parts of the valves are manufactured out of commercial plastics, from PAGF to PPGF, with seals made out of Viton (FKM). Additionally, to avoid overpressure inside the loop, each the reservoir and upstream tanks have a spring-loaded safety valve AH-SV-32504. The valve is made out of stainless-steel grade 1.4404 with FKM seals and opens through overpressure and closes with spring force, and can handle fluids, gases and vapors. It operates between gauge pressures of $0.5 \cdot 10^5$ to $10 \cdot 10^5$ Pa with a flow capacity between 0.0014 and 0.0059 kg/s. The pressure relief valves are connected to the tanks through special DN32 grooved nuts with internal milk thread RD 58 × 1/6" for cone sockets dimensioned after DIN 11851 and manufactured out of stainless-steel grade 1.4301. Three flanged ball valves of the type CHZ06 are used for filling/emptying the facility (one flanged ball connects the reservoir tank to the main closed loop and a second one connects the main closed loop to the sump tank). Once the fluid is drained out of the facility during maintenance or inactive periods, it can be temporarily stored in the sump tank which has a total capacity of 0.39 m³. The fluid can then be redirected to the reservoir tank through a vertical submersible centrifugal pump of the type RT3 16/200 with a maximum head and volumetric flow rate of 16 m and 0.004 m³/s. The pump is very compact and all wetted parts are made out of plastics PP and PVDF, with seals made out of FKM. The maximum and minimum submersible levels are 0.357 m and 0.0885 m, and the fluid has no contact with any metal component (like the impellers) since the pump is installed vertically. Both the reservoir and optical container tanks are connected to the submersible pump via four G1½" threaded ball valves of the type K2 with a nominal pressure of PN64. All of the aforementioned valves are manufactured out of stainless-steel grade 1.4408 with PTFE seals. All pipes, flanges and tanks are being manufactured from stainless-steel grade 1.4571. The pipeline was dimensioned following the DIN EN 10216-2 standards and the minimum wall thickness for the stainless-steel pipes was calculated through the relation

$$t_{min} = t_v + c_1 + c_2 \quad (2)$$

where t_v is the required minimum wall thickness without allowances and tolerances, c_1 is the surcharge to compensate for the permissible wall thickness shortfall and c_2 is the corrosion or erosion allowance [Wittel et al. (2013)]. All the stainless-steel pipes have a wall thickness from 0.0035 m to 0.0045 m and are capable of withstanding pressures between $8.5 \cdot 10^5$ and $57 \cdot 10^5$ Pa, respectively. The PP and borosilicate pipes were dimensioned with

$$t_{min} = \frac{P_G \cdot d_a}{2 \cdot \frac{K}{S} + P_G} \quad (3)$$

where d_a is the outer diameter of the pipe, K is the creep strength at the operating temperature, and S is a safety factor [Wittel et al. (2013)]. For polypropylene, $S = 1.3$ as there are no cyclic loads and neither paraffin oil nor ethyl benzoate dissolve polypropylene [Wittel et al. (2013)], and K was provided by the pipe's manufacturer. For borosilicate glass, the ratio $K/S = 7$ N/mm² following the permissible stress in accordance with DIN EN 1595. Both DURAN and PP pipes have a wall thickness of 0.005 m and can withstand pressures of up to $6.6 \cdot 10^5$ Pa and $9.5 \cdot 10^5$ Pa, respectively. All flanges were dimensioned according to DIN EN 1092-1 and are of the type welding neck flanges with sealing M/F faces for a nominal pressure PN16. The gaskets were dimensioned following the DIN 2690 standards and are of the type PTFE virginal mounted through IBC and SR connections. The pipe bends were dimensioned following the DIN 2605 guidelines and have a 90° bending angle and a radius of 0.114 m. Final considerations for the construction of the facility include structural support and safety. In order to mount, distribute the weight and provide mechanical support, Bosch aluminum profiles of the type 45 × 45 and 45 × 90 are used with additional sponge-rubber padding on the bottom to insulate the facility from mechanical vibrations and compensate for surface irregularities on the floor. Three OG130 rubber compensators made out of PTFE are also used to isolate the main loop from possible vibrations generated by the reservoir tank and the centrifugal pump. The Bosch profiles include polypropylene pipe supports with U-clamps of the type RB dimensioned after DIN 3570 to secure the pipe line and to provide appropriate guidance. Additionally, in order to enclose the laser areas due to the PIV measurement systems, the facility is built inside a room with steel plate walls suitable for class 3B and 4 laser operations and with laser safety curtains certified according to EN 60825-4. To filter out contaminants from the closed loop and protect instrumentation, a strainer valve of the type SFFL is mounted downstream of the centrifugal pump. Finally, for rupture and spillage mitigation, two secondary containment barriers will be mounted around the reservoir tank and the primary loop (seen in Fig. 4). The barriers are manufactured out of stainless-steel and mechanically fastened and sealed to the laboratory floor to ensure leak-tight containment.

The selection of construction materials for the facility was primarily governed by the chemical compatibility requirements associated with the oil-ester mixture in order to ensure the structural integrity and long-term stability of the experimental setup. Paraffin oil consists of saturated hydrocarbons while ethyl benzoate is an ester aromatic ring. They are both non-polar fluids (which allows the formation of a uniform, single-phase solution) that exhibit negligible reactivity toward metals but can significantly affect, depending on the operating temperature, a broad range of polymers. Prolonged exposure to the oil-ester mixture may induce polymer swelling, softening and environmental stress cracking to PMMA, TPE, PVC, LDEP, PETG or certain rubbers (silicone, EPDM, NBR or SBR). Additionally, the facility is treated as a low-pressure process installation rather than a fully pressure-rated vessel and piping system in order to reduce manufacturing complexity for thicker walls, stronger welds and tighter tolerances. Throughout the aforementioned Reynolds number range, the gauge pressure never exceeds $0.5 \cdot 10^5$ Pa.

3. Control system of the facility

A temperature sensor of the type iTHERM TM131 will be installed at the settling chamber through a G $\frac{1}{2}$ " male threaded connection in order to measure the inlet temperature T_{in} . This sensor has an immersion length of 0.050 m and a measuring range between -223.15 and 473.15 K. With the T_{in} measurements, the dynamic viscosity (PPDS equation), the density (Rackett equation) and the vapor pressure (Antoine equation) of the fluid can be calculated through the following correlations

$$\frac{\mu_{mix}}{\text{Pa} \cdot \text{s}} = E_1 \cdot \exp \left[A_1 \cdot \left(\frac{C_1 - T_{in}}{T_{in} - D_1} \right)^{1/3} + B_1 \cdot \left(\frac{C_1 - T_{in}}{T_{in} - D_1} \right)^{4/3} \right] \quad (4)$$

$$\frac{\rho_{mix}}{\text{kg/m}^3} = \frac{A_2}{B_2^{1 + (1 - T_{in}/C_2)^{D_2}}} \quad (5)$$

$$\ln \left(\frac{P_{v,mix}}{\text{Pa}} \right) = A_3 + \frac{B_3}{T_{in} + C_3} \quad (6)$$

where the inlet temperature is measured in Kelvin [VDI (2010)]. As the facility will operate at 20 ± 5 °C, the equations are appropriate for data reproduction since there is no need to extrapolate to high temperatures. For higher accuracy, both the dynamic viscosity and density will be experimentally determined before the experimental campaign starts with a rotational rheometer and with a thermomechanical analysis (TMA), each with a measurement uncertainty of ± 5 % and ± 0.5 %, respectively.

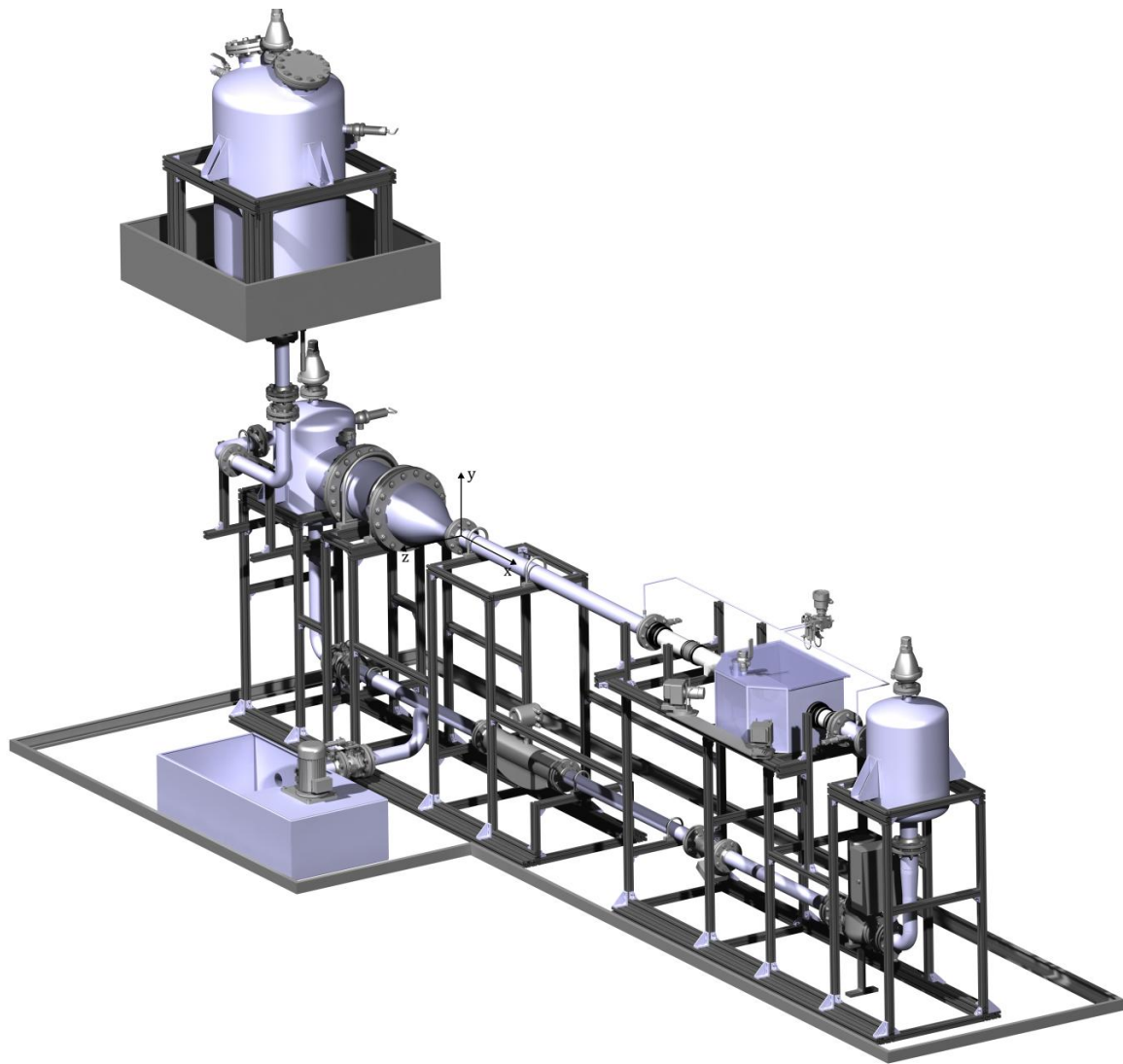


Figure. 4 Isometric view of the complete closed loop facility.

Because throttle control drives operation away from the pump's best efficiency point and since the loop requires relatively low head at high volumetric flow, variable-speed control was selected as the preferred strategy [EDUR (2017)]. Accordingly, a frequency controlled centrifugal pump will be installed in the main closed loop to span $5000 \leq Re \leq 50000$. The pump is of the type EBPI 80-160 with a maximum head and volumetric flow rate of 9.7 m and $0.019 \text{ m}^3/\text{s}$, respectively, and a control frequency between 14.0 to 50.0 Hz. The housing, impeller and shafts are manufactured out of stainless-steel grade 1.4408 and 1.4462, and the seals out of FKM. The frequency control unit is of the type KFU-tronic 2.2 with a rated output power of 2.2 kW and output current of 5.6 A. The selected pump covers the required Reynolds number operating points without the need to either construct a bypass line nor to connect a second pump in parallel/series. The frequency converter will be controlled by a customized LabView software where the user-defined control variable will be the Reynolds number based on the inner diameter of the test section

$$Re = \frac{D \cdot \dot{m}}{A \cdot \mu_{mix}} \quad (7)$$

The mass flow rate $\dot{m}$ will be obtained through a Coriolis mass flow meter of the type FCB450. All wetted components are built out of stainless-steel 1.4404 and the casing out of cast aluminum. The mass flow meter has a nominal size of DN80, a maximum mass flow rate of 30 kg/s, and a calibration of 0.10 % for the mass flow rate and 2 kg/m³ for the density. All temperature sensor, pressure sensors, Coriolis mass flow meter and frequency controller operate with a 4-20 mA analog current signal to transmit sensor data. The frequency controller analog signal is recorded through a C series 4-channel NI-9265 output module, while the remaining signals are recorded through a C series 8-channel current input NI-9253 module. The timing, synchronization and data transfer between the C series modules is controlled through an 8-slots cDAQ-9187 ethernet chassis.

4. Conclusion

A new closed loop facility is being constructed at KIT in order to study the turbulent flow field inside a pipe roughened with variously structured ribs in order to characterize the mean flow field, the rib-induced turbulent transport and the secondary flow field. The construction process of the closed loop was introduced and a detailed description of the primary components and the necessary instrumentation to measure the mass flow rate, pressure, temperature and velocity were presented. The facility operates in a Reynolds number range of $5000 \leq Re \leq 50000$, with bulk flow velocities of $0.19 \leq u_{B,T} \leq 1.93$ m/s at the test section and up to a maximum gauge pressure of $0.5 \cdot 10^5$ Pa. To resolve the optical distortion caused by the curvature of the pipe walls, a low viscosity paraffin oil-ethyl benzoate mixture is used to equal the refractive index of borosilicate glass. PP and DURAN glass were selected as suitable materials to construct the test section due to the high optical transparency and lower refractive index value of DURAN and due to the chemically inert properties of both polypropylene and glass against the oil-ester mixture.

References

Abdel-Wahab, S. and Tafti, D. (2004). Large Eddy Simulation of Flow and Heat Transfer in a 90 deg Ribbed Duct with Rotation: Effect of Coriolis and Centrifugal Buoyancy Forces. *Journal of Turbomachinery*. **126**, 627-636. <https://doi.org/10.1115/1.1791648>

- Budwig, R. (1994). Refractive index matching methods for liquid flow investigations. *Experiments in Fluids* **17**, 350–355. <https://doi.org/10.1007/BF01874416>
- Castro, I.P., Kim, J.W., Stroh, A. and Lim, H.C. (2021). Channel flow with large longitudinal ribs. *Journal of Fluid Mechanics* **915**, A92. <https://doi.org/10.1017/jfm.2021.110>
- Laws, E.M. and Quazzane A.K. (1995). A further investigation into flow conditioner design yielding compact installations for orifice plate flow metering. *Flow Measurement and Instrumentation* **6**, 187-199. [https://doi.org/10.1016/0955-5986\(95\)00007-9](https://doi.org/10.1016/0955-5986(95)00007-9)
- Pump Manufacturer EDUR (2017). *EDUR Pump Guide for Centrifugal Pumps*. Edur.com, www.edur.com/en/service/pump-guide. Accessed April 2024
- Fang, X., Yang, Z., Wang, B.C., Tachiem N.F. and Bergstrom, D.J. (2015). Highly-disturbed turbulent flow in a square channel with V-shaped ribs on one wall. *International Journal of Heat and Fluid Flow* **56**, 182-197. <https://doi.org/10.1016/j.ijheatfluidflow.2015.07.008>
- Kang, C. and Yang, K.S. (2016). Characterization of Turbulent Heat Transfer in Ribbed Pipe Flow. *Journal of Heat and Mass Transfer* **138**, 041901. <https://doi.org/10.1115/1.4032150>
- Kang, C. and Yang, K.S. (2017). Heat Transfer Enhancement in Turbulent Ribbed-Pipe Flow. *Journal of Heat and Mass Transfer* **139**, 071901. <https://doi.org/10.1115/1.4035712>
- Labbé, O. (2013). Large-eddy-simulation of flow and heat transfer in a ribbed duct. *Computer & Fluids* **76**, 23-32. <https://doi.org/10.1016/j.compfluid.2013.01.023>
- Ruck, S. and Arbeiter, F. (2021). LDA measurements in a one-sided ribbed square channel at Reynolds numbers of 50,000 and 100,000. *Experiments in Fluids* **62**, 232. <https://doi.org/10.1007/s00348-021-03313-5>
- Tropea, C., Yarin, A. and Foss, J. (2007). *Springer Handbook of Experimental Fluid Mechanics*. Springer Berlin, Heidelberg. <http://doi.org/10.1007/978-3-540-30299-5>
- VDI (2010). *VDI Heat Atlas* (2nd edition). Springer Berlin, Heidelberg. <http://doi.org/10.1007/978-3-540-77877-6>
- Wittel, H., Muhs, D., Jannasch, D. and Voßiek, J. (2013). *Roloff/Matek Maschinenelemente*. Springer Vieweg. <https://doi.org/10.1007/978-3-658-02327-0>
- Wright, S.F., Zadrazil, I. and Markides, C.N. (2017). A review of solid–fluid selection options for optical-based measurements in single-phase liquid, two-phase liquid–liquid and multiphase solid–liquid flows. *Experiments in Fluids* **58**, 108. <https://doi.org/10.1007/s00348-017-2386-y>
- Zhang, Z. (2004). Optical guidelines and signal quality for LDA applications in circular pipes. *Experiments in Fluids* **37**, 29–39. <https://doi.org/10.1007/s00348-004-0781-7>