Smart pig for hydraulic roughness measurement in a pipeline

Pressure Loss Reduction Program

And Inside Pipeline Corrosion Monitoring

The device described in this document works on the same principle as the device used for measuring the aerodynamic performance of the inner surface of a cylindrical wall (internally coated or not) mounted in a pressurized casing (figures 1 and 2). Description of this device may be found in patent 44 721 and also in this web site - Theme "Flow Friction" – Section "Coating aerodynamic test".

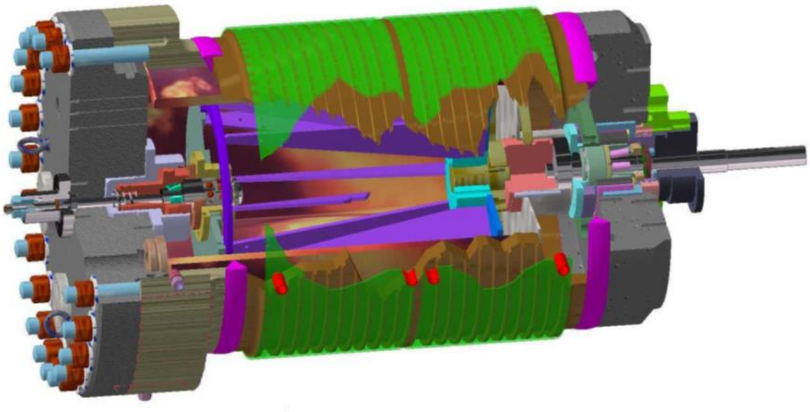
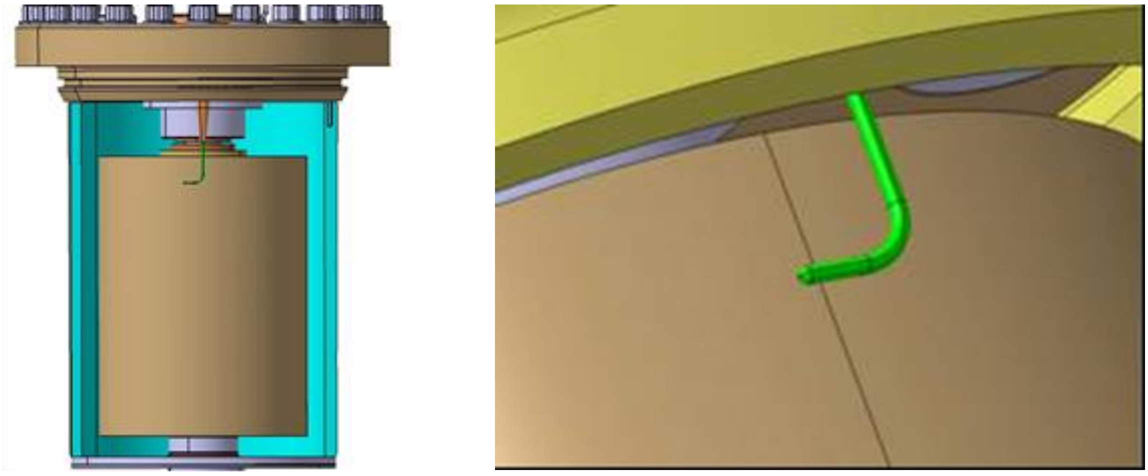


Figure 1 - Rotating Cylinder Unit for measuring the hydraulic roughness of the internal surface of a pipe section – Test unit with the flanged high pressure cover (left) used for inserting a 14 inch pipe section whose hydraulic roughness has to be evaluated.



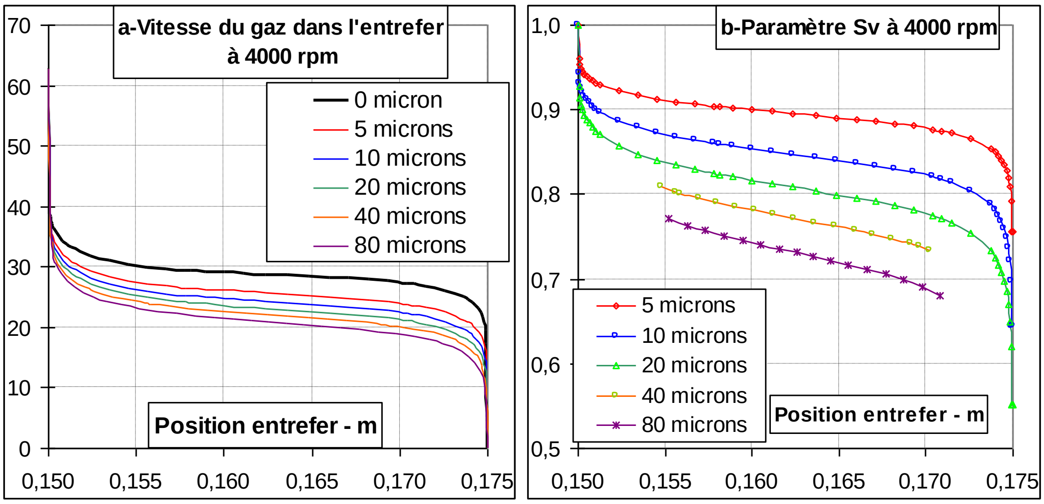
Figures 2 a & b – Cross section of the Rotating Cylinder Unit with the rotating cylinder (brown colour) and the fixed cylindrical wall (blue - left figure) and the Pitot tube mounted in between the rotating cylinder and the fixed wall (right figure).

The Smart Pig device is intended to be motioned inside a pipeline, from the inlet to the outlet (or pigging stations), by the pressure difference existing between the two pipe ends but also between the two ends of the device. **It is intended to be used mostly for the measurement of the hydraulic roughness on the inner wall of the pipe** (figure 3).

Figure 3 – Typical roughness profile with definition of the Ra and Rz parameters.

The device is designed to operate in **single phase flow** either with gas or liquid. It could physically operate in two phase flow but operation of sensors could be erratic. Operation with gas or liquid requires different geometrical (cylinder diameter) and operating conditions (rotating speed) considering the differences in fluid properties, mainly density and viscosity.

The device consists of a frame mounted on wheels in contact with the inner wall of a pipe, a membrane located upstream for the propulsion of the device and at least one cylinder rotating in a plane perpendicular or parallel to the axis of the pipe (figures 7 to 13). The cylinder is in most cases driven by an electric motor powered by batteries mounted inside the frame.



Figures 4 a & b – Gas velocity between rotating cylinder and fixed wall for several roughness values of the fixed wall versus the distance between the two surfaces (left figure). Non dimension velocity parameter versus the distance between the two surfaces (right figure).

In the following, the gas is taken as an example. During its rotation, the cylinder drives the gas which in turn is slowed down by the fixed pipe wall. The slowdown of the gas could be **measured by a torque meter** mounted on the drive shaft of the rotating cylinder, the resisting torque varying in the same direction as the roughness of the fixed wall. The fluid velocity profile established between the rotating cylinder and the internal of the pipe wall, being a function of the pipe wall roughness (figures 4 and 5), the intermediate gas velocity may also be **measured by a Pitot tube** or any other anemometric device.

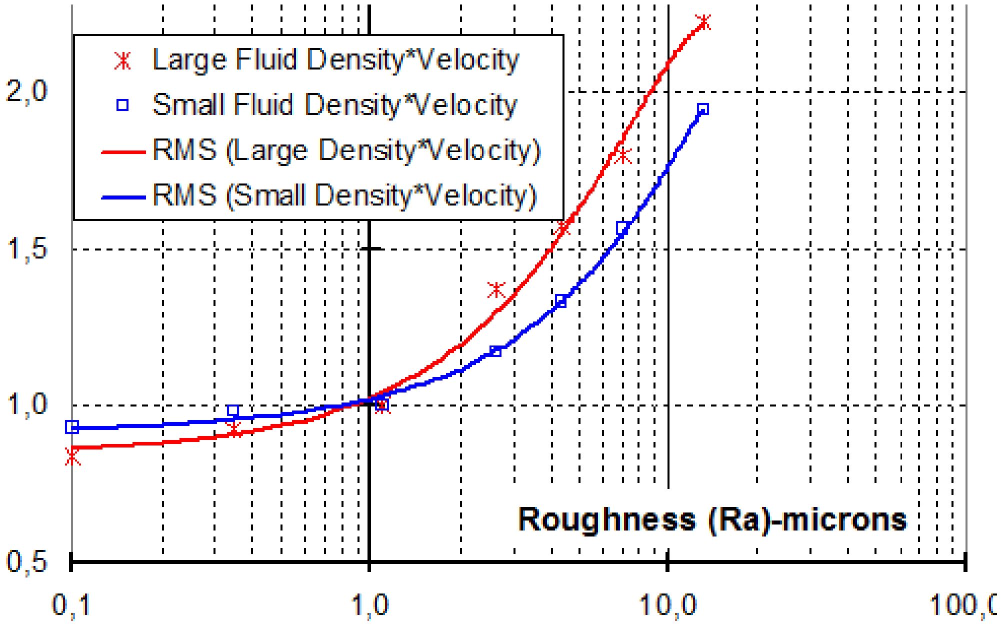
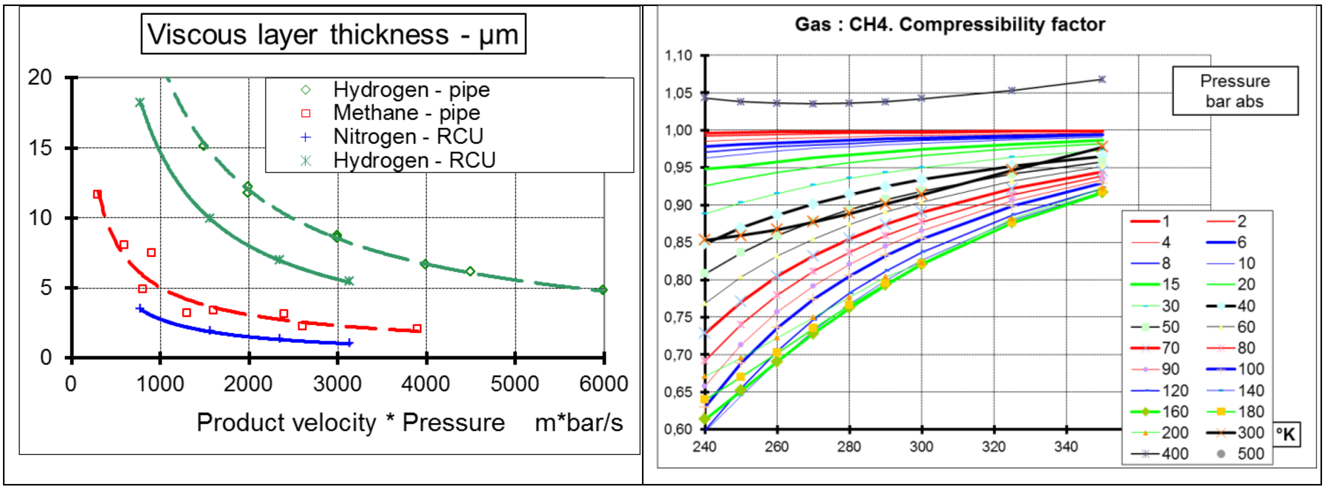


Figure 5 – Pitot tube measurements between the rotating cylinder and the fixed wall for two conditions of Reynolds number (Density * Velocity product)

The torque meter provides a global (circumferential) measurement of the roughness at the measuring section while the Pitot tube provides a local measurement on the circumference of the pipe. The cylinder – pipe wall gap is of the order of 20 to 40 mm although it is possible to reduce or increase this interval. A small distance will allow an increase in the sensitivity of the measurement, in particular, by using a torque meter. A greater distance will avoid contact with the walls, particularly, by using a Pitot tube.



*Figures 6 a & b – Viscous layer thickness versus the (Velocity * Pressure) parameter (left figure) and compressibility factor (i.e. density or volumetric mass) for methane (right figure).*

The speed of rotation of the cylinder is defined by the degree of roughness to be measured. The more, one wants to detect low values of roughness, the more it is necessary to reduce the thickness of the viscous layer next to the fixed wall and, consequently, the more the speed must be increased at the periphery of the rotating cylinder. Given the operating conditions of the pipe, one can estimate a peripheral velocity of the rotating cylinder of the order of 5 times the gas velocity in the pipe (figure 6a).

To give an example, **with the Rotating Cylinder Unit** (figures 1 and 2) **it is possible to measure a wall roughness ranging from 0.1 to 100 µm (Ra)**.

The pipeline device can include several rotating cylinders. In this case, the direction of rotation of one group of cylinders will preferably be opposite to that of the other group in such a way that the total torque of the assembly around the pipeline axis is as close as possible to zero, thereby avoiding the rotation of the frame. Each rotating cylinder can be equipped with its own torque sensor which therefore provides some redundancy of the torque measurements but also a measurement adapted to a particular range for each torque meter. Each rotating cylinder can also be equipped with several Pitot tubes allowing a roughness measurement at several angles in a pipe section. The Pitot tubes are mounted at regular intervals with a slight offset from those of the adjacent sections so as to sweep the interior section of a pipe as regularly as possible.

In the case of a single rotating cylinder, to avoid the rotation of the frame, the inertia of the rotating cylinder is chosen as small as possible and the weight of the frame as large as possible. In addition, the equipment may be designed in a way that the center of gravity of the assembly is as low as possible (away from the axis of rotation) and that the reaction torque of the cylinder is less than about half of the overturning torque. This torque corresponds to a positioning of the center of gravity of the frame on a horizontal line passing through the center of rotation.

To avoid the use of electric motors, **the drive of the rotating cylinders may be achieved by the passage of gas through the frame** and then through fins mounted inside the rotating cylinder.

Each Pitot tube is connected to a differential pressure sensor for the measurement of the dynamic pressure. The device is also provided with one or several pressure and temperature sensors for calculating the density (volumetric mass) of the gas (figure 6b). The knowledge of the dynamic pressure then the gas density allows the calculation of the gas velocity at the location of the Pitot tube. The device is also equipped with a measurement of the rotating speed for each cylinder. All the measurements are registered in a recording unit for later data analysis (figures 7 to 13).

The device is preliminary calibrated by spinning the rotating cylinder in a closed pressurised tube of small length (still gas - zero axial velocity) **of given roughness**. This calibration can be done for several values of speed of rotation and gas pressure. **The ratio of the gas velocities corresponding to each wall** (circumferential velocity relative to the rotating cylinder divided by the circumferential velocity relative to the fixed wall) **is established as a function of the local Reynolds number** (Re nb) of the channel separating the fixed part from the rotating part (Re nb = gas velocity * hydraulic diameter * gas density / absolute gas viscosity). There is a single curve of the circumferential gas velocity ratio for each roughness value. As a consequence, **during operation in a pipe** and after conversion of the operating conditions of the pipe to the local Reynolds number (between the fixed and the rotating wall), **the calculation of the velocity ratio provides the equivalent roughness of the pipe.**

The device can also be calibrated during an axial displacement of the cylinder set in rotation. A shift in the velocity ratio curve may occur in relation with the axial displacement of the device (or rotating cylinder). Alternatively, if the device cannot be moved, a gas recirculation may be applied in a closed volume to simulate the relative axial displacement of the device (or rotating cylinder).

The equipment may be used either within a pressure loss reduction program or for internal corrosion monitoring. In both cases, it will consist in measuring the local hydraulic roughness. In the first case, it provides the value of a local friction factor. In the second case, the hydraulic roughness may be converted to physical roughness (Ra, Rz or Rq) to provide an indication of the surface degradation and therefore of the internal corrosion. The system may be designed to make measurements at any circular and axial position according to the data acquisition system capability.

The **geometrical design** depends on many parameters (pipe diameter, fluid density, viscosity and velocity). The design is specific to each application. As an example, for the simulation of industrial gas pipelines operating between 50 to 500 bar pressure and 2 to 10 m/s gas velocity, a 12 inch cylinder (rotating) mounted in a 14 inch pipe (static) has been used. The rotating speed of the cylinder is dependent on the roughness magnitude that has to be measured. In one case, it has to be run at 3000 rpm for detecting roughness values of the order of 0.1 µm. Should 1 µm be sufficient, rotating speed may be reduced down to 300 rpm. The **electrical consumption** is dependent on above parameters (rotating speed) but also on the availability of an external energy supply (for instance, cylinder driven by the main fluid). As an average, the order of magnitude would be of 1 kW without any fluid energy supply. However, this needs to be reviewed in conjunction with pipe and monitoring specifications. The cylinder torque is obviously determined by the absorbed power and the rotating speed.

No need to mention that the **economics** depend on much more parameters that the ones quoted above. Economics have been carried out for several gas pipeline applications and for many different operating conditions (selection of pipe diameter, operating pressure and internal coating). Some examples may be given: a) First example: pipe 160 km long – 32 inches – 70 bar at first compressor inlet and 150 bar at second compressor outlet. By reducing the wall roughness from 30 to 10 µm, the corresponding fuel gas saving represents approximately 6 million US$ over a 30 year period. b) Second example: pipe 180 km long – 36 inches – 150 bar at pipe inlet. By reducing the wall roughness from 30 to 10 µm, the corresponding fuel gas saving represents approximately 11 million US$ over a 30 year period.

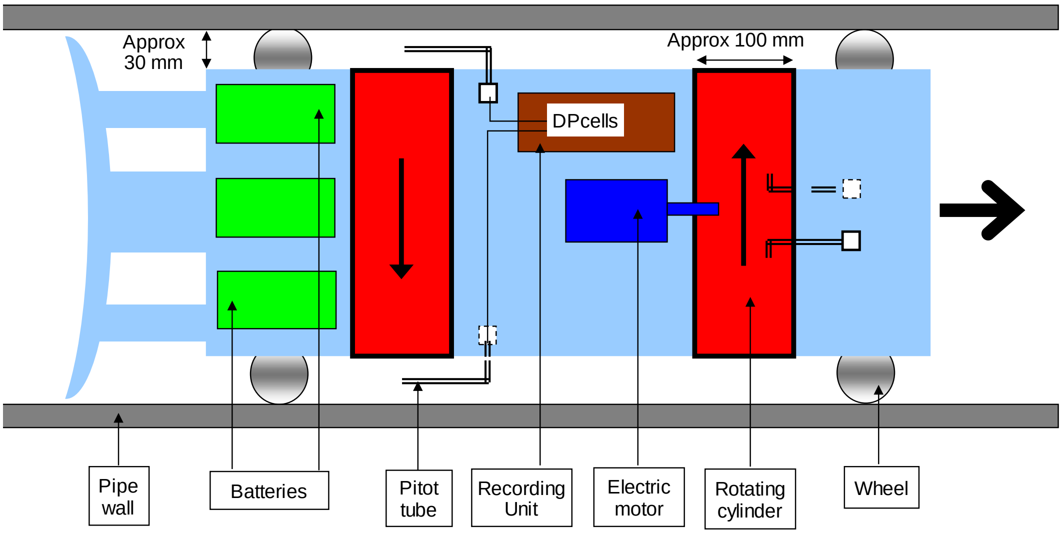


Figure 7 - Typical arrangement of apparatus for internal pipe monitoring with ***radial cylinders*** *– Pipeline transversal section*

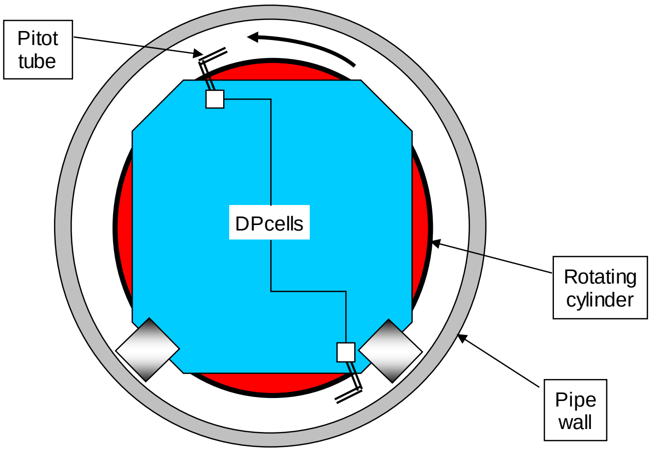


Figure 8 - Typical arrangement of apparatus for internal pipe monitoring with ***radial cylinders*** *- Pipeline cross section*

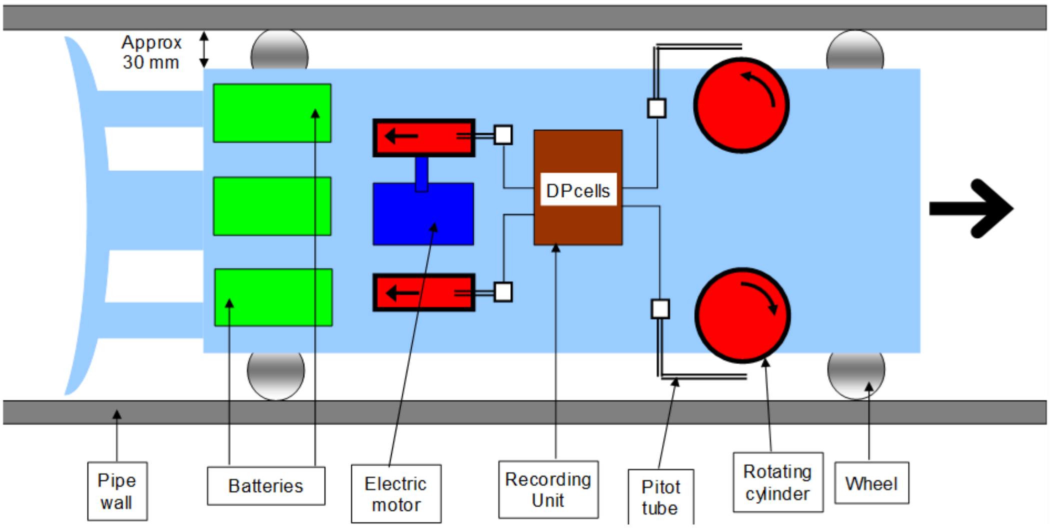


Figure 9 - Typical arrangement of apparatus for internal pipe monitoring with ***axial cylinders*** *- Pipeline transversal section*

The proposed monitoring equipment can also be used to record **local fluid operating conditions**. Fluid Mechanics data (friction factor, pressure drop, etc ...) and Thermodynamic SOFTWARES (dew point margin, hydrate formation margin, phase equilibrium, etc ..) may be obtained from different sources for interpretation of recorded data. As an example, relation between water condensing and roughness / corrosion increase could be established as a result of this analysis. Finally, the proposed monitoring equipment could be associated to a MFL monitoring system.

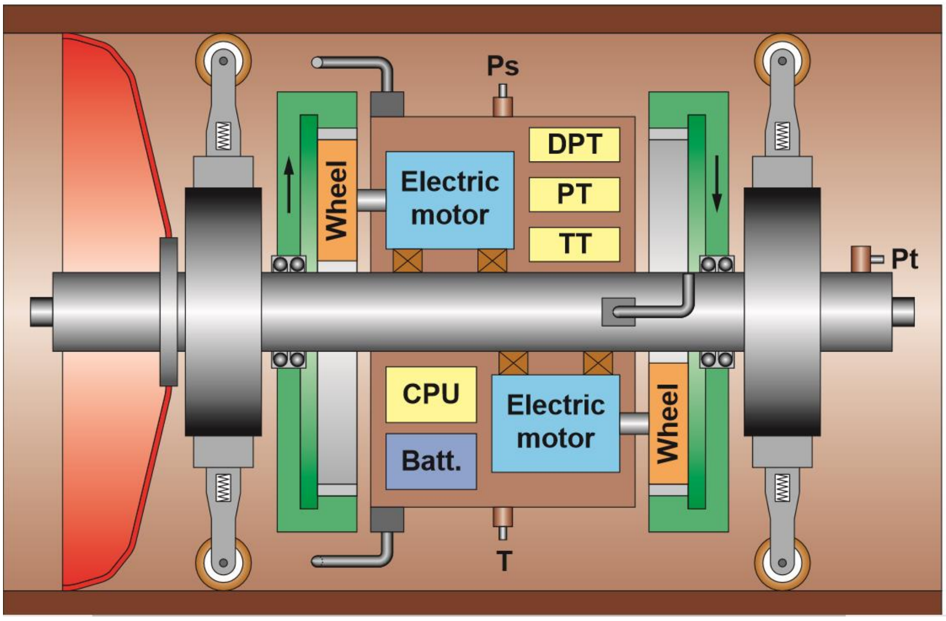


Figure 10 - Typical arrangement of apparatus for internal pipe monitoring with ***radial cylinders****, various sensors and control units – Pipeline transversal section*

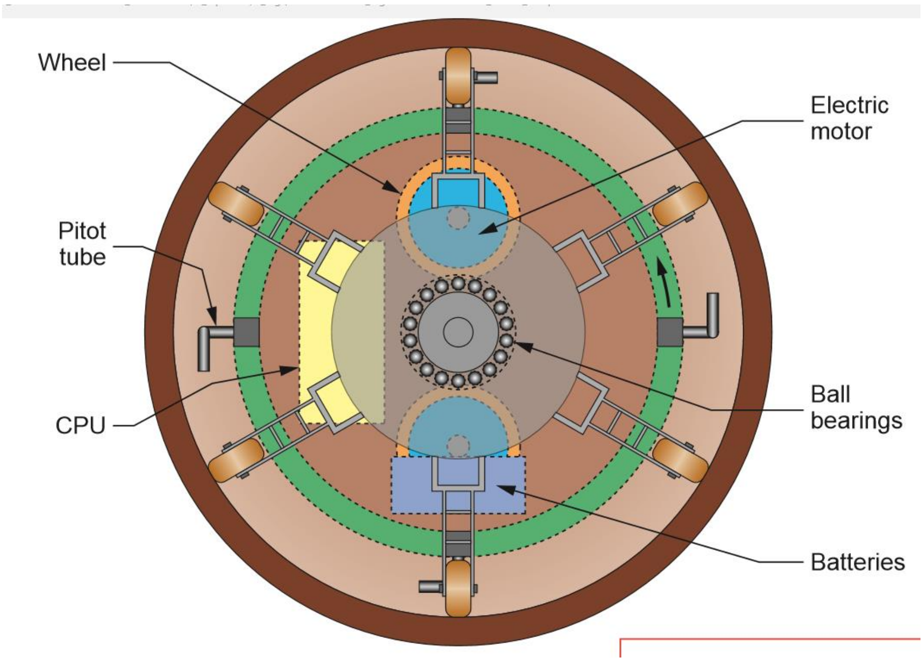


*Figure 11 - Typical arrangement of apparatus for internal pipe monitoring with **radial cylinders** - Pipeline cross section*

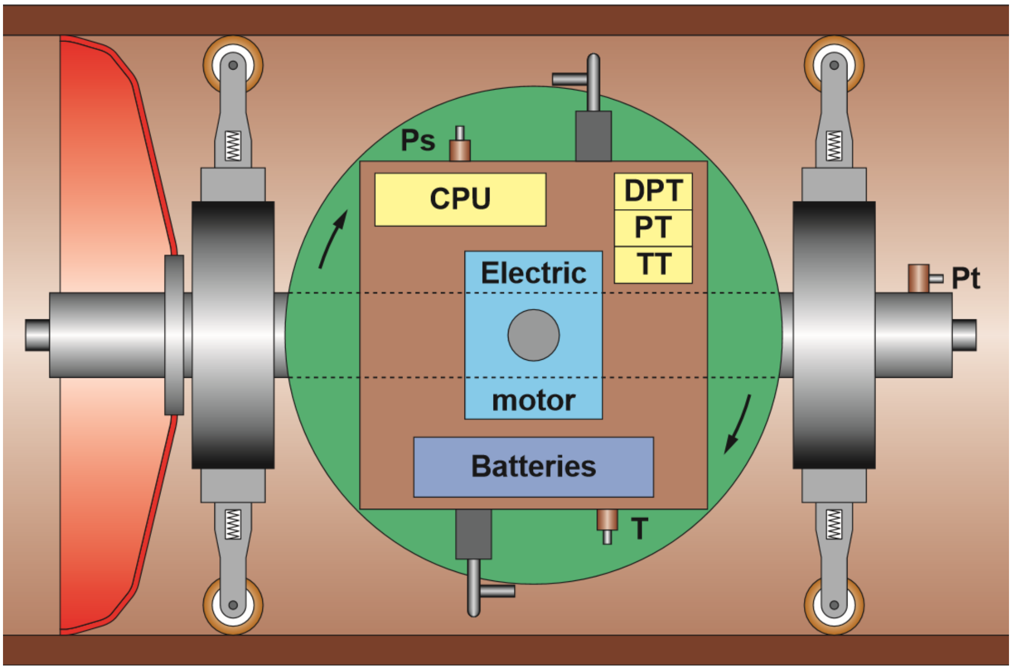


*Figure 12 - Typical arrangement of apparatus for internal pipe monitoring with **axial cylinders,** various sensors and control units - Pipeline transversal section*

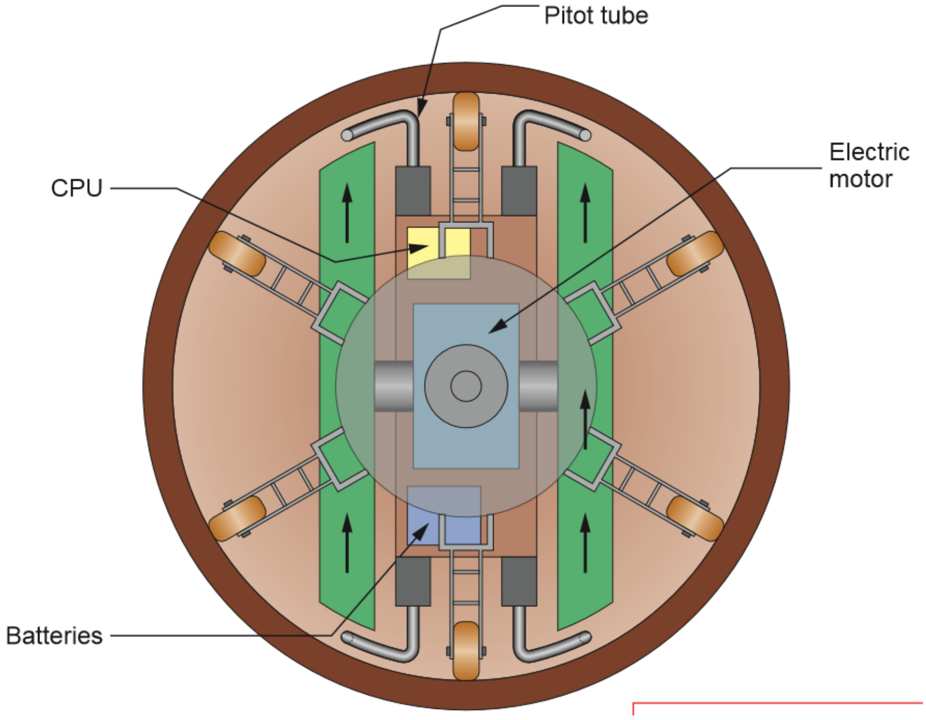


Figure 13 - Typical arrangement of apparatus for internal pipe monitoring with ***axial cylinders*** *- Pipeline cross section*