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Thermodynamic Efficiency Measurements
The energy distribution in the boundary layer at the turbine inlet

by

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SUMMARY

The distribution of specific mechanical energy in the flow entering a turbine is a point of uncertainty in thermodynamic efficiency measurements. However, experience has shown that this distribution is very even over the flow cross section, and in most cases a single water sampling point in the flow is sufficient to measure a good average of the specific mechanical energy in the turbine inlet. Two field tests are described where the sampling probe protusion was varied to investigate the distribution of specific mechanical energy. Both tests confirm that the distribution is even.

RÉSUMÉ

Il existe une incertitude quant à la répartition de l'énergie mécanique massique de l'écoulement à l'entrée de la turbine dans la méthode thermodynamique de mesure du rendement des turbines hydrauliques. Néanmoins l'expérience a demontré que cette répartition de l'énergie est tres égale dans l'ecoulement. Deans la plupart des cas il suffit d'utiliser un seul point de soutirage à l'entrée de la turbine pour obtenir une moyenne de l'énergie mécanique massique. Deux essais sur place sont decrits à-dessous, ou on a fait variér la distance de l'orifice de la sonde à la paroie intérieure de la conduite afin d'étudier la répartition de l'énergie mécanique massique. Les deux essais confirment que la répartition de l'énergie est égale.

Introduction

The turbine efficiency is the power output/input ratio of the machine. The input can be expressed as the hydraulic energy available to the turbine, - specific hydraulic energy E (energy per unit mass of water passing through the turbine). The turbine output is the mechanical power delivered to the turbine shaft, which according to the law of conservation of energy, can be found as the difference in specific mechanical energy E_m (energy per unit mass of water passing through the turbine) between the inlet and the outlet of the turbine.

Measurement of specific hydraulic energy $E=g\cdot H_n$ is simply a determination of the turbine net head H_n. However, the thermodynamic measurement of the specific mechanical energy

$$E_m = a\cdot\Delta p + C_p\cdot\Delta T + 0.5\cdot\Delta V^2 + g\cdot\Delta z$$

is more challenging. Total head probes are used to take water samples into heat insulated measuring vessels at defined elevations (z) where the pressures (p), temperatures (T) and velocities (V) are measured. The gravity constant (g) and the physical properties of water, i.e. specific heat (C_p) and isothermal factor (a), are taken from tables in the test code IEC 41-1991., Ref. (4). The mechanical energy E_m is sometimes also called "total entalpy", which is entalpy i (= $a\cdot\Delta p + C_p\cdot\Delta T$) plus velocity and elevation terms.

The ideal procedure would be to explore the whole conduit cross section to find the average specific mechanical energy in a flow, but practical experience has shown that a limited number of sampling points are required. This is specified in the test code, Ref. (4). The turbine inlet cross section normally has an even E_m distribution. The outlet, however, requires a more comprehensive survey over the cross section to find the average E_m. This article concentrates on the inlet cross section.

Objective

For turbine inlet sections with diameter less than 2.5 m and a certain staight pipe length ahead only one sampling probe is required. The test code,(Ref. (4)), chapter 14.7, says:
"The systematic uncertainty due to absence of exploration of energy distribution can amount to ± 0.2 % of the specific mechanical energy on the turbine high pressure side, and ± 0.6 % on the low pressure side."
For practical reasons and to avoid discussions these figures are often used in the analysis of uncertaity.

To demonstrate that ± 0.2 % uncertainty is relevant for the inlet section, a couple of examples from actual tests are described. One is from about 1965, Ref. (1) when the "partial expansion procedure" was used, and the next is from 1996 with the "direct procedure". The latter procedure is much faster, and consequently it is less senstive to variation of temperature with time in the water flowing into the turbine.

Case 1: Francis turbine with inlet diameter 1500 mm and 240 m head.

The sampling probe was located between the spherical valve and spiral inlet, and the protusion of the probe could be varied from 0 to 180 mm (0 - 0.12·D). The measuring vessel for temperature and pressure was incorporated in the probe so that no heat exchange could disturb the measurements. The reference measuring vessel with thermometer in the tail race was kept in the same positon throughout the tests.

Figure 1 shows the results. The specific energy E is converted to head of water H. (H = E / g where g is the gravity constant). The upper curve in the diagram is the local hydraulic energy measured as stagnation pressure at the tapping orifice of the probe. Thus the curve represents the velocity profile in the flow. The line below is the wall pressure taken from four piezometer taps at the measuring section. The lowest series of points are the most interesting ones as they are showing the measured mechanical energies at the five locations. They are all within a band of ± 0.17 % (± 0.38 m) of the aveage mechanical energy, which is slightly less than than the uncertainty of ± 0.2 % indicated in the test code, Ref. (4).

At that time (1965) the test code, IEC 41-1963, Ref. (2) specified that the draw-off hole (orifice) of the probe preferably should be at a distance from the wall of about one-seventh of the conduit diameter, i.e. about 0.15·D. In this experiment the maximum probe protusion was 0.12·D, but there was little reason to believe that 0.15 and 0.12 made any significant difference. More interesting was that the mechanical energy seemed to be constant even very near to the wall. The explanation, why the mechanical energy profile differs from the hydraulic energy profile, is that heat energy is generated from shear in the boundary layer, and that heat energy compensates for the lower velocity energy near the conduit wall.

Based on experiments like this done by several test engineers the next edition of the test code, IEC 607-1978, Ref. (3) specified that the distance of the orifice from the internal wall of the conduit should be at least 0.05m. In the diagram Fig.3 the 0.05 m means 0.033·D. The latest test code, IEC-41-1991, Ref. (4) specifies the same minimun distance of 0.05m.

Case 2: Pelton turbine with inlet diameter 700 mm and 470 m head.

A new test was made with modern test equipment to look into this problem a second time over a wider range of relative protusion (0 - 0.25·D) and at a higher hydraulic head. The temperature of the water entering the turbine was very stable which made the test conditions favourable. **Figure 3** shows the sampling probe with integrated "measuring vessel" for pressure and temperature.

Figure 2 shows the results in a similar diagram as for Case 1. The two upper curves: the local hydraulic energy (probe stagnation pressure) and the energy level of the conduit wall pressure show the flow velocity profile. The mechanical energy profile is seen below, and it is quite even. One probe orifice location was at the conduit wall (only half of the 10 mm orifice was inside the conduit). This point at L/D=0 has a slightly higher mechanical energy than the others. The total variation of the five test points is within ± 0.07 % (± 0.28 m) of the average mechanical energy, which is well below the uncertainty of ± 0.2 % indicated in the test code, Ref. (4).

From looking more in detail at the mechanical energy points in the diagram, it appears that the two inner points (more than 0.1·D away from the wall) are slightly below the average line. The three points nearer to the wall (in the boundary layer) are near or above the average line. Interesting, but this variation is too small to have any practical effect on the test results.

Conclusion

The two tests, performed to investigate the mechanical energy profile in the flow entering the turbine, confirm that the estimated uncertainty of ± 0.2 % of E_m in the test code , Ref. (4), is relavant for heads above 200 m and smaller conduit diameters (less than about 2 m), see **Figure 4**. The diagram shows the absolute unceratainty of our two test results, and lines indicating relative uncertainty of ± 0.1 and ± 0.2 % . The order of magnitude of the absolute uncertainty of the two tests is the same, less than 0.4 m (which is equivalent to about 1 mK in water temperature difference).

There might be found some additional variation of E_m if measurements were performed along other radii in the test section, but when the turbine inlet conduit has a good hydraulic design this variation will most probably be very small.

Larger conduit diameters will normally have less uniform inflow caused by bends, bifurcations etc.. Therefore the upper limit of 2.5 m conduit diameter for one probe, recomended in the test code, seems reasonable.

References

(1) OFTEBRO, Ivar: “Practical Thermodynamic Efficiency Measurements” (in Norwegian), Teknisk Ukeblad, Maskin, No. 16, 1969, Oslo.

(2) IEC Publication 41 - 1963, “International code for the field acceptance tests of hydraulic turbines”, Genève 1963.

(3) IEC Publication 607 - 1978, “Thermodynamic method for measuring the efficiency of hydraulic turbines, storage pumps and pump-turbines”, Genève 1978.

(4) IEC Publication 41 - 1991, “Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines”, Genève 1991.

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(4) IEC Publication 41 - 1991, "Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines", Genève 1991.

Fig. 1
ENERGY DISTRIBUTION AT THE TURBINE INLET
Francis turbine
H = 240 m
D_i = 1500 mm

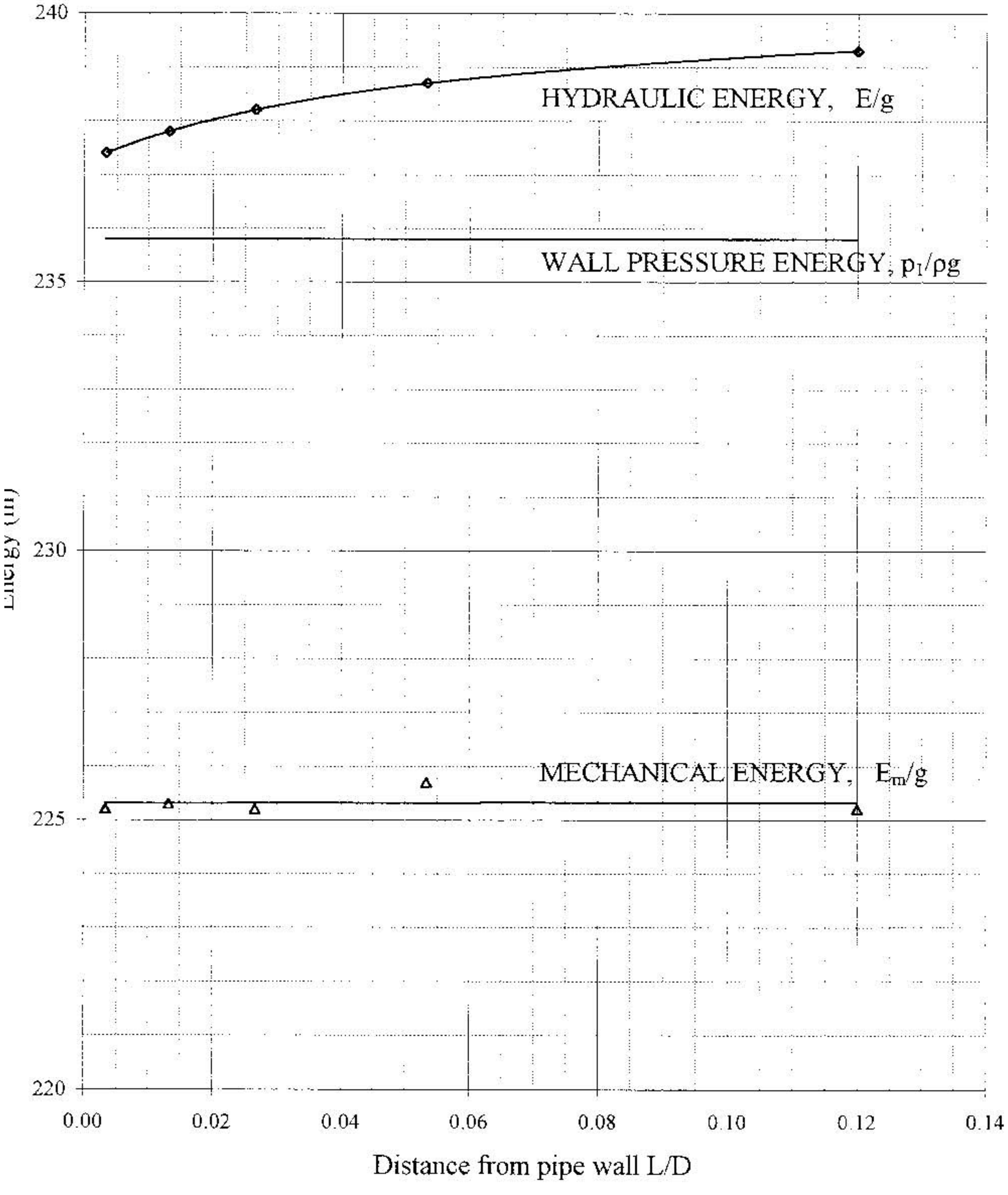
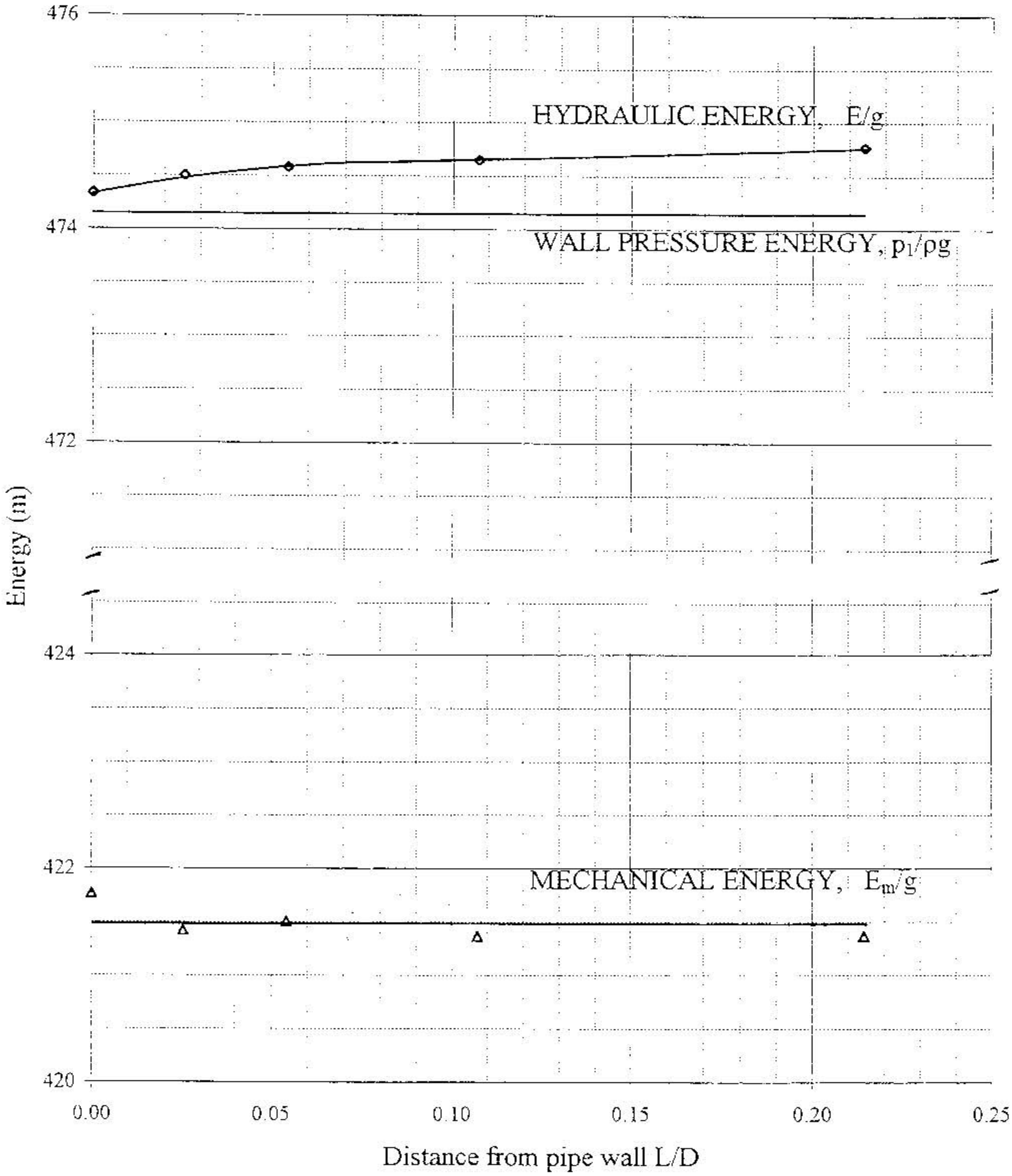


Fig. 2
ENERGY DISTRIBUTION AT THE TURBINE INLET
Pelton turbine
H = 470 m
D_i = 700 mm



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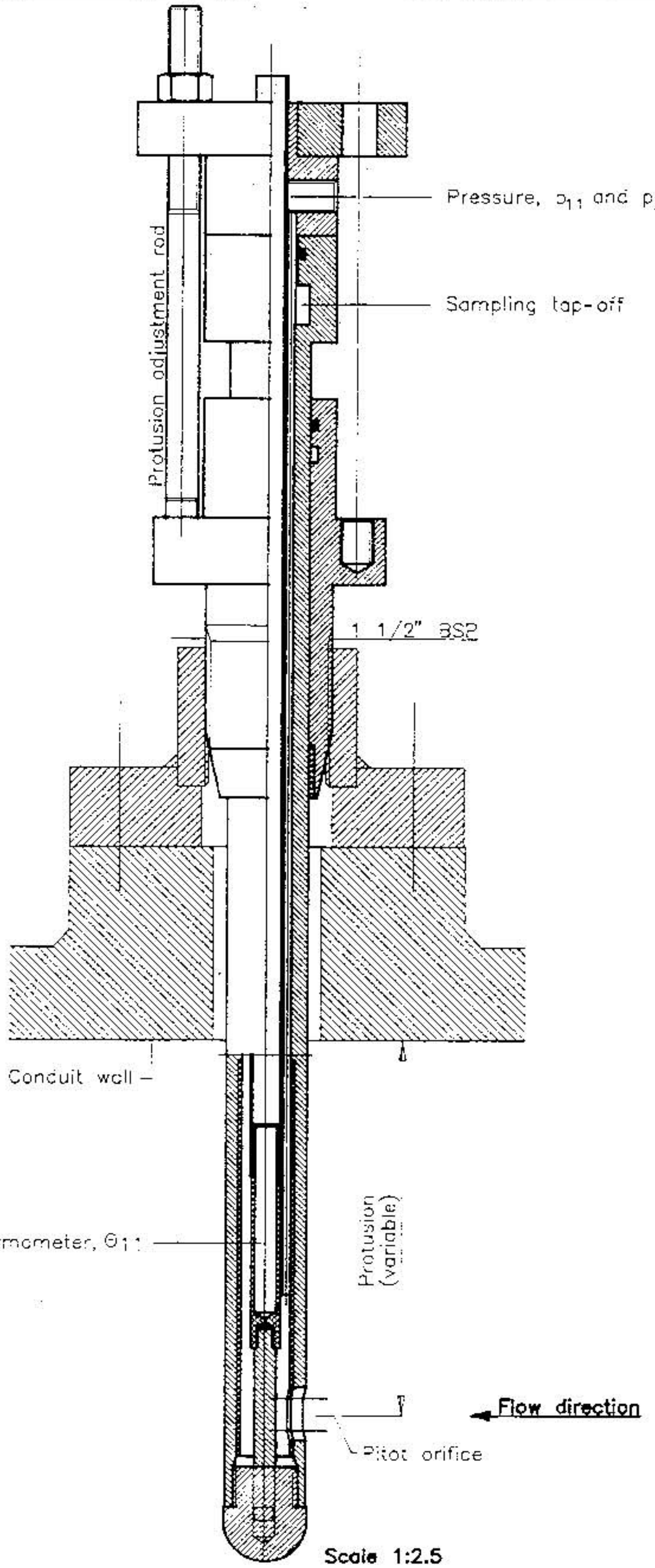
Sak: **Fig. 3** THERMODYNAMIC SAMPLING AND MEASURING PROBE			



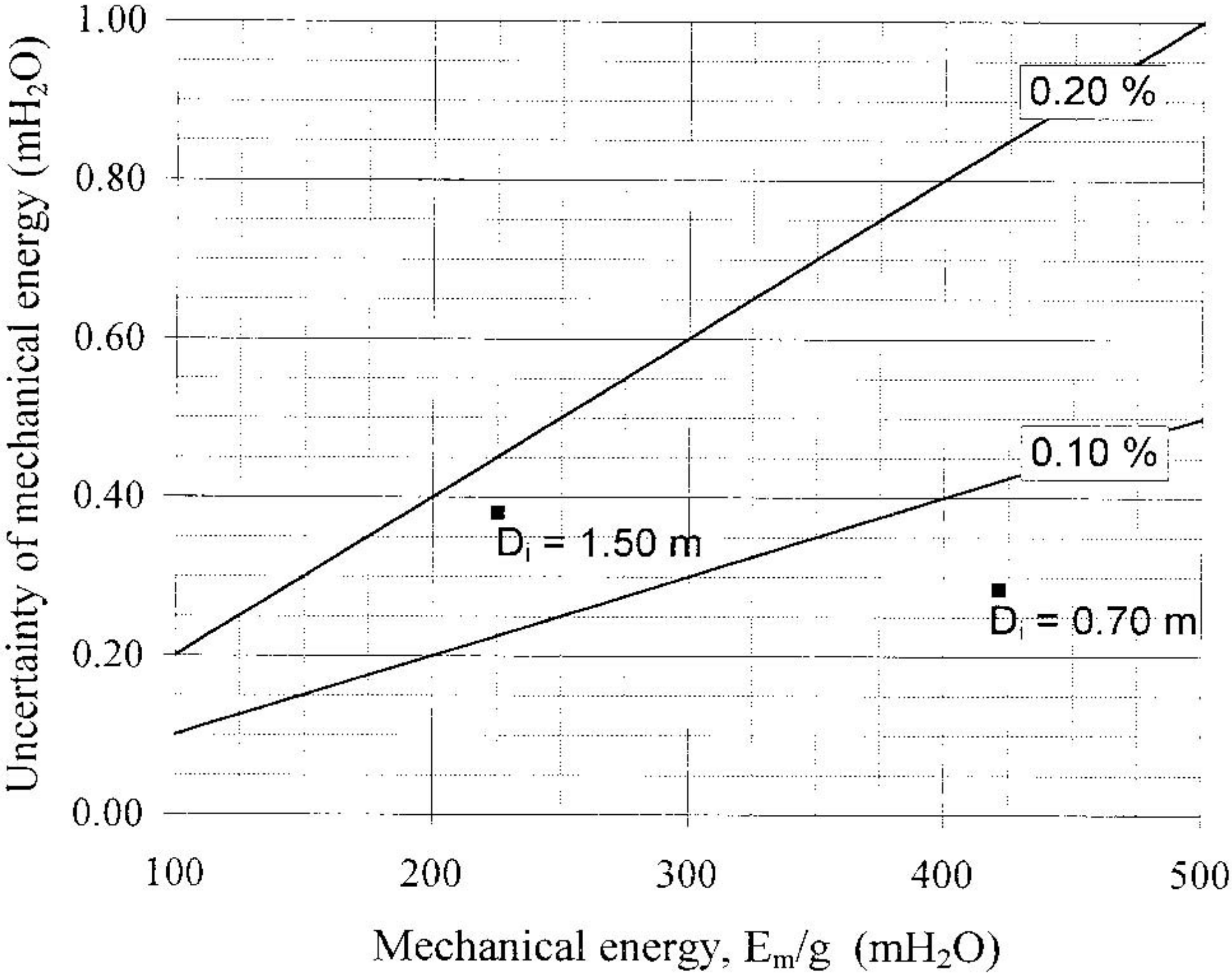


Fig. 4 Uncertainty of mechanical energy