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EXPERIMENTALLY DETERMINED HYDRAULIC CHARACTERISTICS OF HEU AND LEU FUEL ASSEMBLIES FOR MARIA REACTOR

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1. INTRODUCTION

To making comparison of hydraulics characteristics for the MR6 type fuel element currently used in MARIA research reactor with CERCA Areva Company fabricated fuel element denoted by MC5 a series of experiments was carried out on the out-of-reactor water test stand specially built for this aim. The tests were performed in a following way:

- Dummy fuel element of MC5 having an identical geometry as the real fuel element to be fabricated by CERCA which didn't contain uranium;
- Fresh fuel element of the MR6 type;
- Fresh MC5 fuel element (one out-of-two fuel elements delivered by CERCA; the test of the second one are to be conducted a bit later).

The presented paper contains description of experiments, defines the course of measurements, sets up the measuring results and encloses the conclusions.

2. MEASURING PROCEDURES

The schematic layout of the out-of-reactor experimental stand together with distributions of measuring points is shown in Fig.1

The coolant flow layout through fuel assembly is shown in Fig. 2.

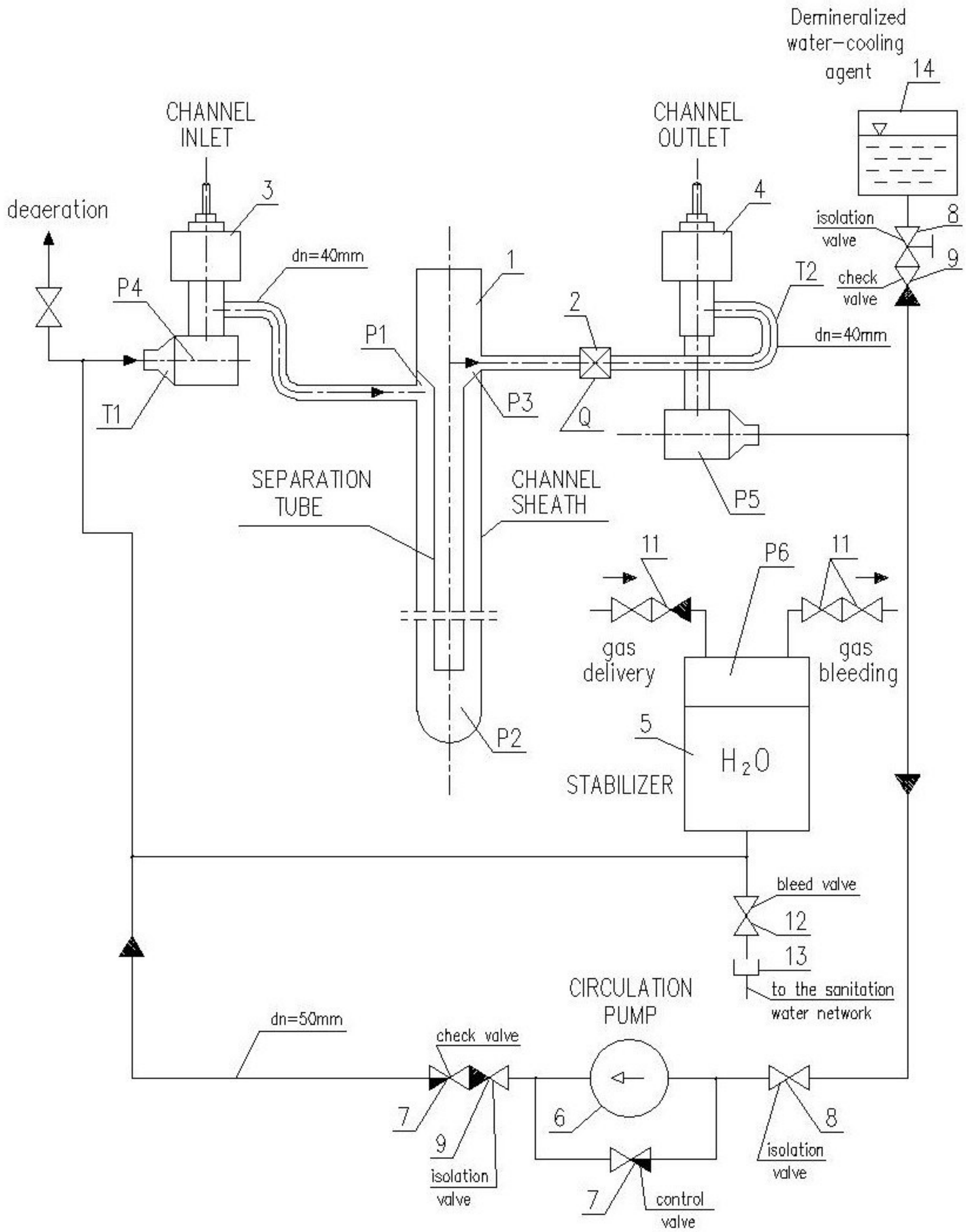

Fig. 1. Schematic layout of test stand along with distributions of measuring points.

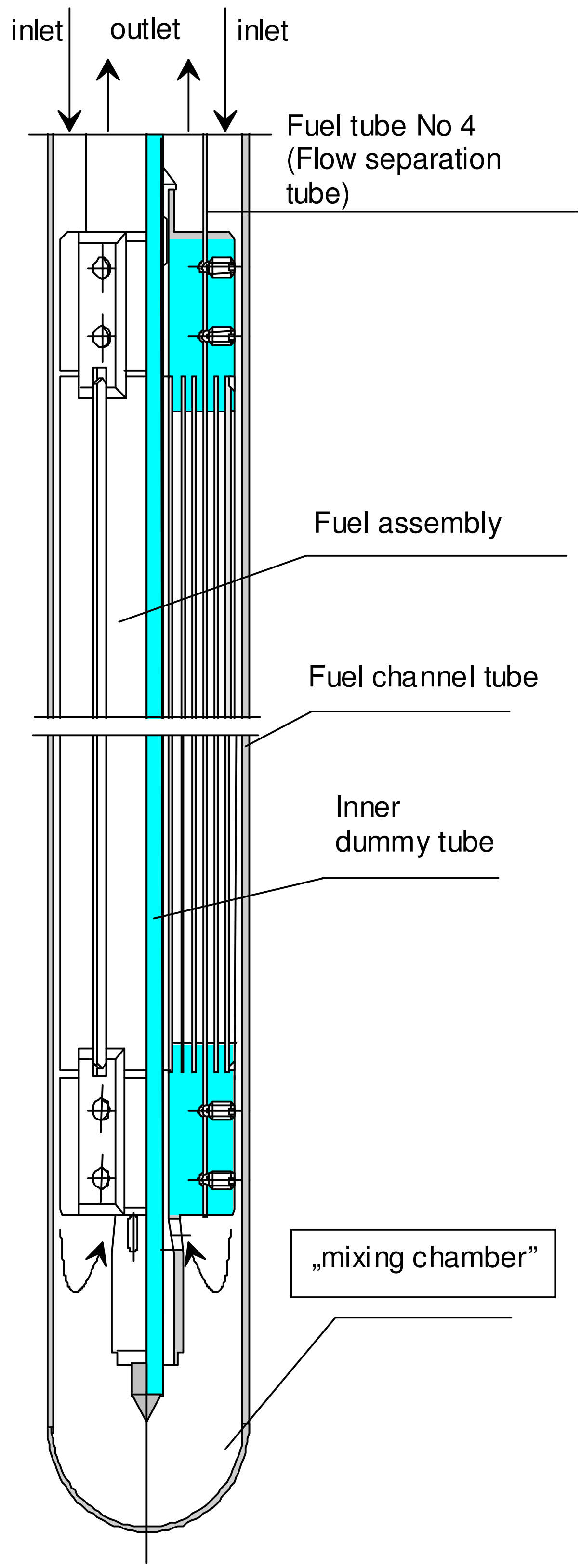

Fig. 2. Coolant flow layout through fuel assembly

In the below described measurements the following measuring points were used:

- Value of volumetric flow rate Q [m^3/h];
- Values of temperatures T_1 and T_2 [°C];
- Values of pressures P_1, P_2, P_3 [MPa].

At the beginning of measuring cycles the dummy fuel element MC5 delivered by CERCA was submitted for examinations on the out-of-reactor test stand. In that period also the hydraulic characteristics of the stand were learned and it was unveiled that the operation of the circulation pump brings about a substantial water temperature rise within the range from 2,2 °C/min (the experimental stand fully thermally isolated) to 1,8 °C/min (after removing of the thermal isolation from the fuel channel outer sheath tube). It is quite understandable since the usable volume of water inside the loop is around 50 l and the thermal power to be transferred into the coolant versus available variation of flow rate is within the range 7 ÷ 14 kW.

This fact imposes the following constraints on experimental procedure:

- In actual situation it is impossible to carry out an isothermal measurement as during the experiment independently on measuring procedure to be used both the temperature and coolant flow rate is being changed;
- Assuming the termination of measuring cycle at water temperature around 80 °C the maximum duration time span of measuring cycle doesn’t exceed around 30 min.

During examination of dummy and real fuel elements there were applied two different measuring procedures.

Procedure I was based on opening and closing the valve in cyclic way at the fuel channel outlet.

Procedure II consisted in recording of influence of water temperature variation on pressure drop and coolant flow rate under fixed position of valves.

During measurements, both according to the procedure I and II in pressurizer was maintained the over pressure on a level of around 1 MPa. Values of data from all measuring points were sampled with frequency of 100 Hz and recorded on hard disk of measuring computer with a span of 1s (as a mean value from 100 samples) or with a span of 0.5 s (as the mean value from 50 samples).

Procedure I brought about cyclic variation of coolant flow rate from zero to maximum value as well the appropriate changes of pressure values. An example of the measuring course to be in compliance with procedure I is shown in Fig. 3.

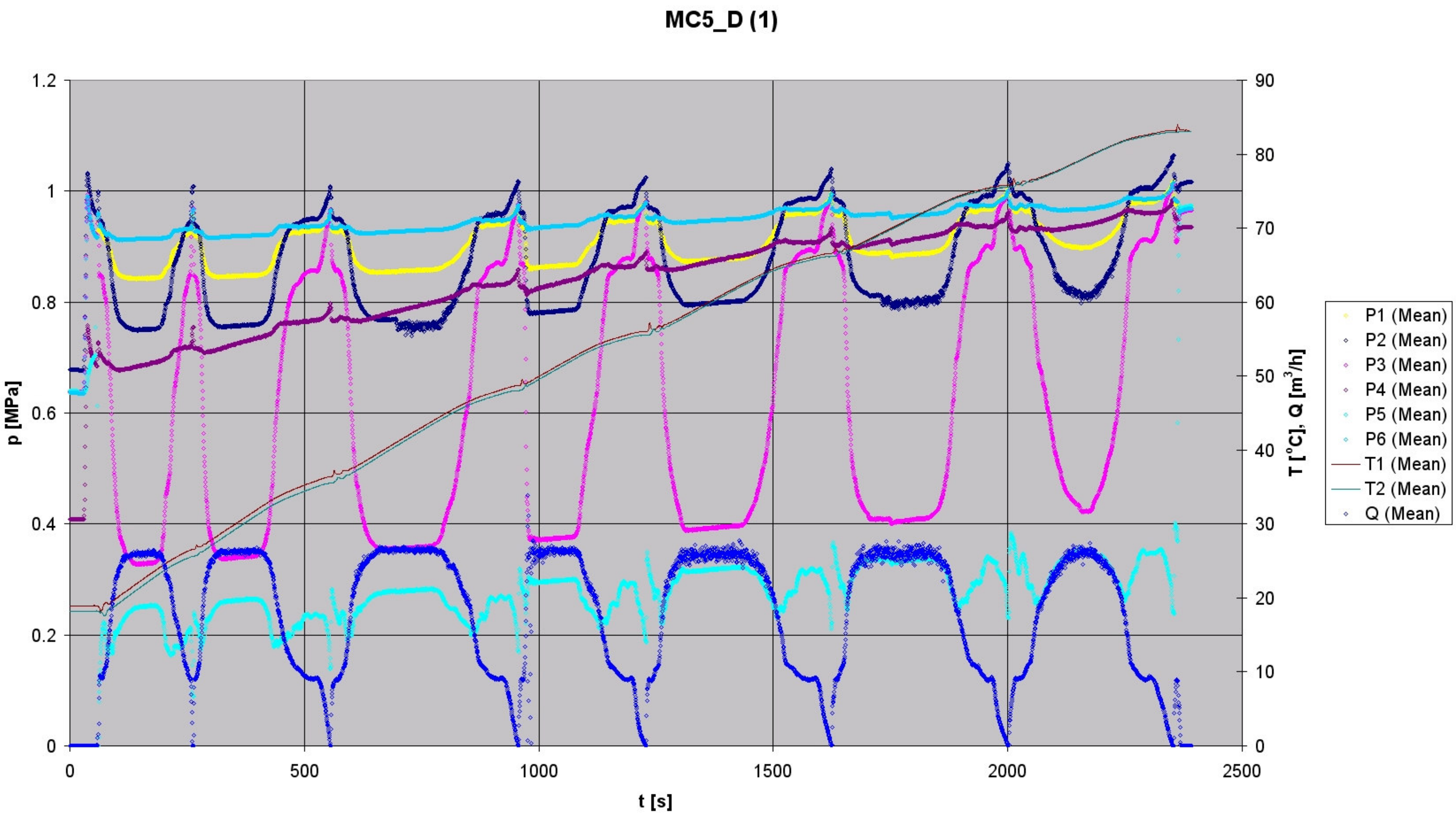

Fig. 3. An exemplifying run of measuring parameters versus time acc. to procedure I

(Dummy fuel element MC5_D)

Fig. 3 depicts also the effect to be caused by nonlinear characteristics of the valve: in spite of slow rotation of valve spindle at the range of flow rate below 10 m^3/h the values of flow rates are being changed very quickly. It brings about to arising of recording errors since the pressure sensors are responding almost without delay but the flowmeter operates with a certain (which is to be setup) response time which leads to arising of errors during recording of fast coolant flow variation. From the other side, extreme slow rotation of the valve spindle causes an elongation of cycle operation: closure phase – opening phase and consequently change of water temperature pending one cycle is to be substantial.

Changing the coordinate system onto $\Delta p = p_1 - p_3 = f(Q)$ and isolation of segments of the recorded data set corresponding to falling and/or rising edges enables to preset the results in more distinct shape (Fig. 4).

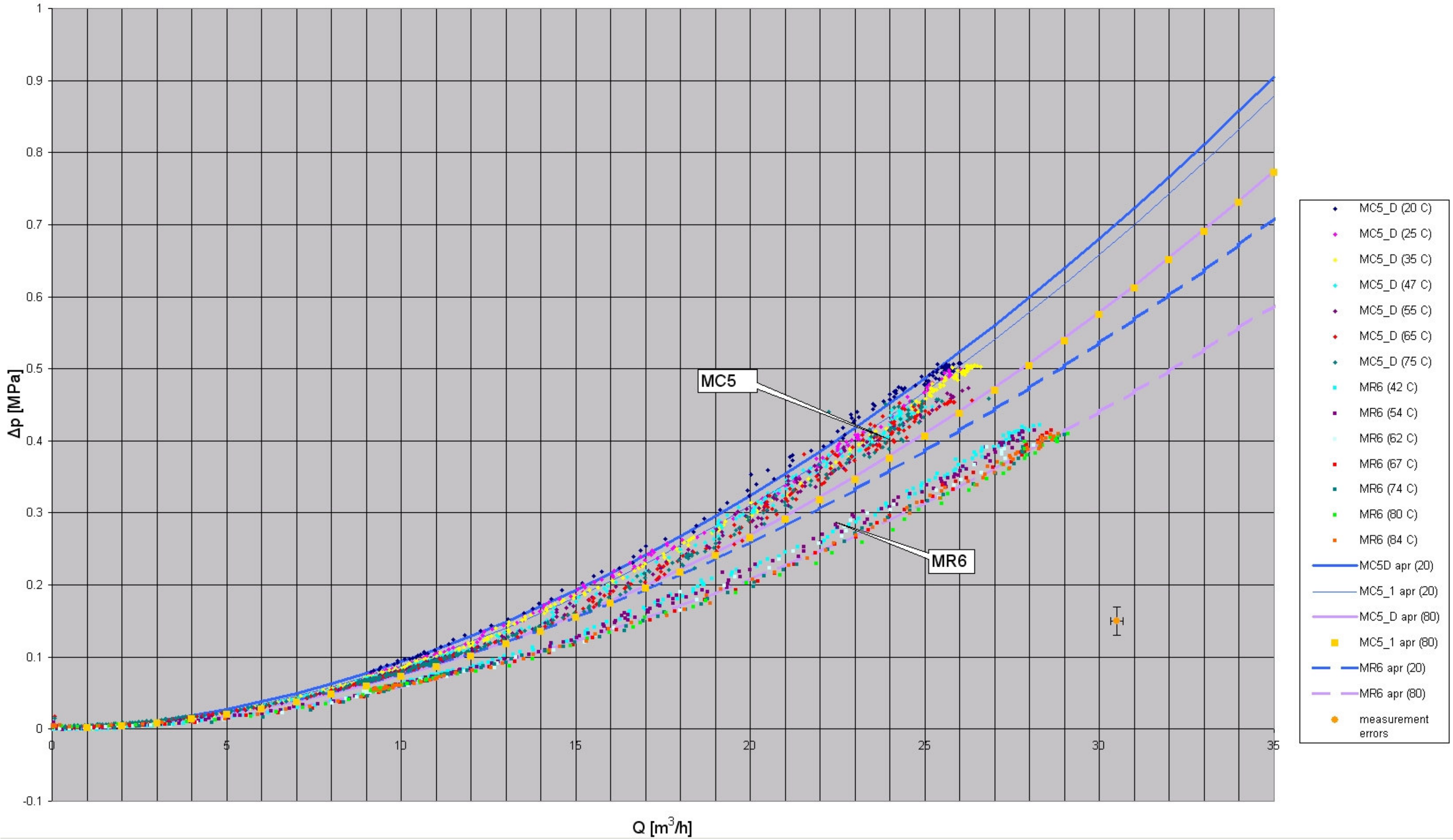

Fig. 4. Measuring results in conformity with procedure I in coordinate system Δp = f(Q)

(Fuel element mock up for MC5 and MR6)

An example of the measuring course to be in compliance with procedure II is shown in Fig. 5.

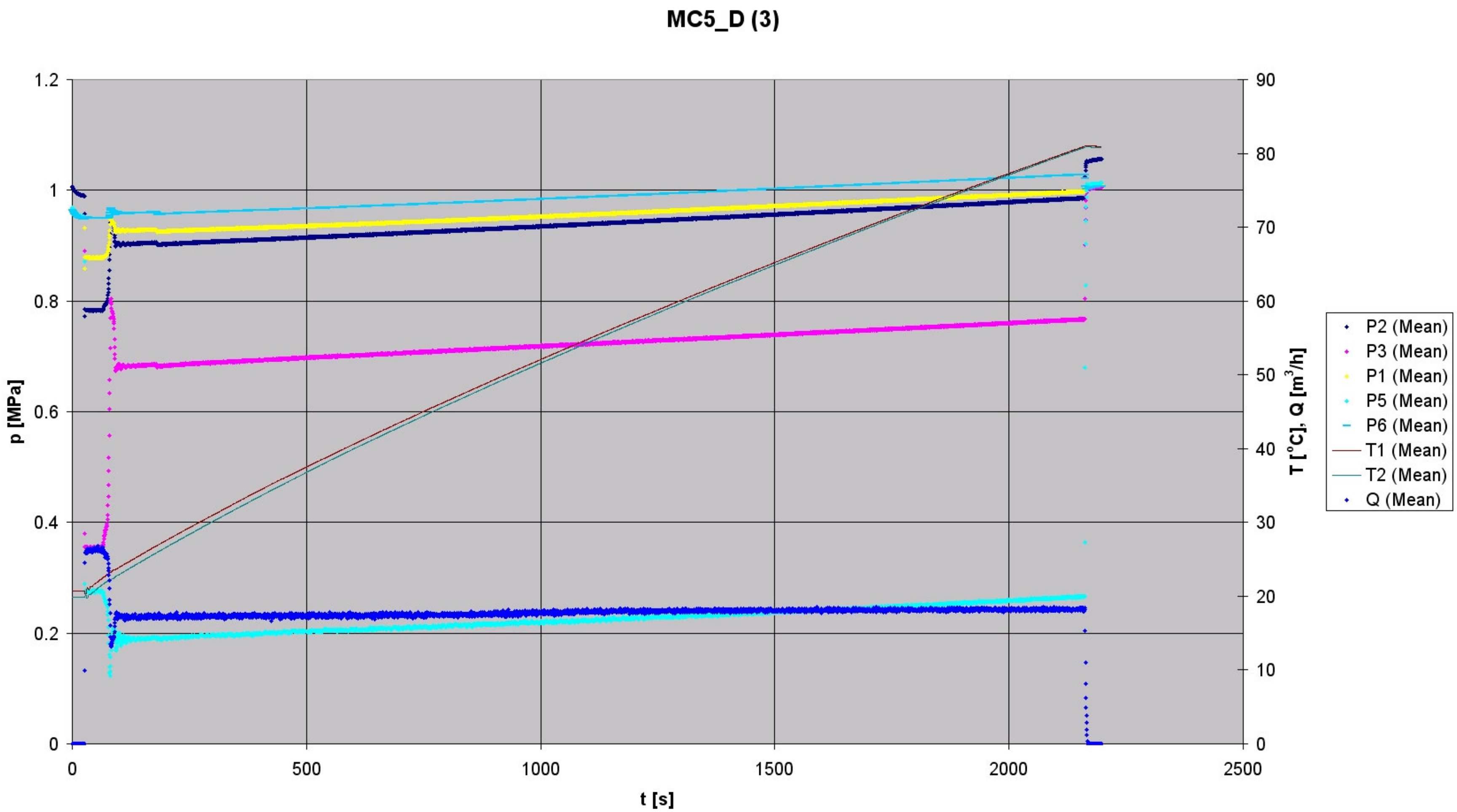

Fig. 5. An exemplifying run of measuring parameters versus time acc. to procedure II

(Dummy fuel element MC5_D)

The findings obtained when performing the above mentioned measuring procedures I and II one could exhibit as a three-dimensional function plot of the two independent variables:

$$\Delta p = f(Q, T)$$

However, it seems to be less understandable and difficult to be used in practice. On the other hand, one can propose another method for presentation of the received results.

The pressure drop in the examined section of the test stand could be presented as a functional relation in a following way:

$$\Delta p = \sum_i \zeta_i \frac{\rho v_i^2}{2} + \sum_j \lambda_j \left(Re_j\right) \frac{\rho v_j^2}{2} = \frac{1}{2} \rho(T) Q^2 \left(\sum_i \frac{\zeta_i}{F_i^2} + \sum_j \frac{\lambda_j \left(Re_j\right)}{F_j^2} \right)$$

where:

ζ_i - coefficients of local hydraulic resistances,

$\lambda_j \left(Re_j\right)$ - coefficients of linear hydraulic resistances,

v_i, v_j – local linear velocities of water,

F_i, F_j – local areas of cross-sections for water flow,

$Re_j = \frac{v_j d_{hj}}{\upsilon(T)} = \frac{Q}{\upsilon(T)} \frac{d_{hj}}{F_j}$ - local Reynolds numbers,

$\upsilon(T)$ - kinematic viscosity of water,

$\rho(T)$ - density of water.

As follows from the above definitions all local values of Reynolds number for the preset geometry of the examined segment are proportional to the value of the quotient $\frac{Q}{\upsilon(T)}$. So, one may illustrate the pressure drop in examined fuel channel as:

$$\Delta p = a \left(\frac{Q}{\upsilon(T)} \right) \rho(T) Q^2$$

or, if passing to the non-dimensional variables,

$$\Delta p = a \left(\frac{Q}{\upsilon(T)} \frac{d_{h\,nom}}{F_{nom}} \right) \rho(T) \frac{Q^2}{F_{nom}^2}$$

where for F_{nom} and $d_{h,nom}$ we take appropriately nominal area of the cross-section and hydraulic diameter of the test stand pipes (d_{nom} = 40 mm).

It enables to formulate an equivalent coefficient of hydraulic resistance **a** for the channel examined as a function of one variable:

$$a\left(\frac{Q}{\upsilon(T)}\frac{d_{h\,nom}}{F_{nom}}\right) = \frac{\Delta p\, F_{nom}^2}{\rho(T)\,Q^2}$$

or:

$$a\left(Re_{nom}\right) = \frac{\Delta p}{\rho(T)\,v_{nom}^2}$$

where $v_{nom} = \dfrac{Q}{F_{nom}}$.

Variability of the kinematic viscosity and water density versus temperature was accounted for by applying interpolating polynomials to be built on values taken from thermodynamic tables of water.

In Fig. 6 the results of all measurements accomplished for the MC5_D mockup, the LTA MC5_1 and presently used Russian fuel of the MR6 type are presented.

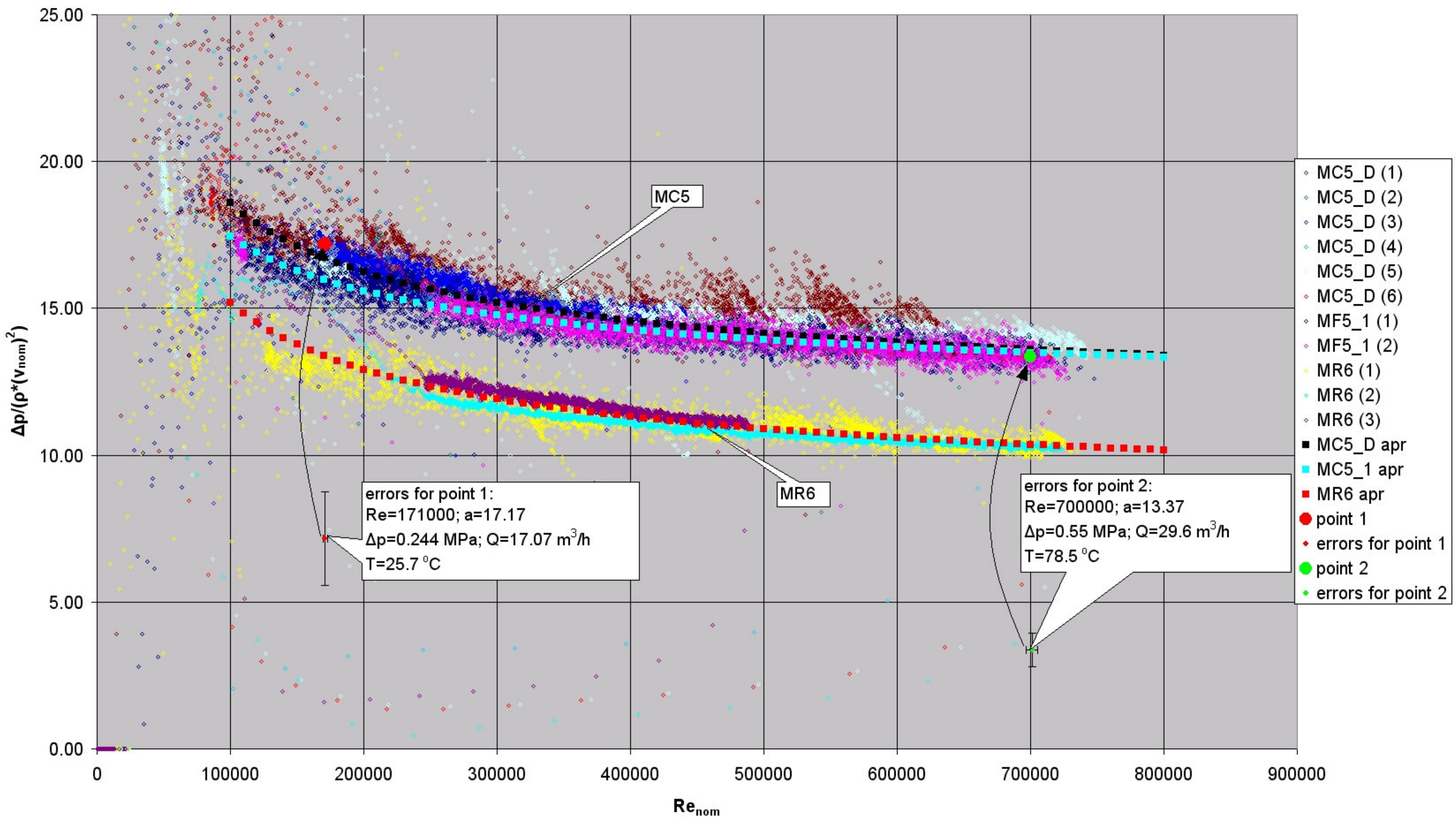

Fig. 6. Measuring results in coordinate system $\frac{\Delta p}{\rho\, v_{nom}^2} = f\left(Re_{nom}\right)$

In Fig. 6 the measuring points for which flow rate values Q < 1 m^3/h (due to the large errors in measurement of flow) were ignored.

Substantial majority of measuring points indicates a large concentration in vicinity of two curves remote from each other: the upper curve corresponds to the measurements accomplished for the dummy fuel element MC5_D and the real fuel element LTA (MC5_1); the lower curve – for the fuel element of MR6 type.

The more accurate analysis to be derived from the data points significantly remoted from the concentration areas enables to identify two major reasons of their scatter:

- Presence of air bubbles at the measurement volume of flowmeter;
- Too fast coolant flowrate variation (recording of activation and disengagement of the circulation pump, change of valve position).

The results taken from measurements performed in accordance with procedure I introduce substantially larger number of scattered points which allows to conclude that they are loaded with significantly greater error than in case of results obtained during procedure II.

In Table 1 the range of parameters variability for individual measurements was set up.

Table 1. Ranges of parametric variability for individual measurements.

Measurement	Procedure	Range T	Range Q
MC5_D (1)	I	18 ... 83	0 ... 27
MC5_D (2)	II	20 ... 80	26 ... 27
MC5_D (3)	II	20 ... 80	17 ... 18
MC5_D (4)	II	20 ... 81	26 ... 27
MC5_D (5)	II	20 ... 80	29 .. 31
MC5_D (6)	II	19 ... 80	28 ... 29.5
MC5_1 (1)	I	20 ... 82	0 ... 31
MC5_1 (2)	II	17 ... 81	28 ... 29.5
MR6 (1)	I	19 … 84	0 … 29.5
MR6 (2)	II	18 … 82	28 … 29.5
MR6 (3)	II	39 … 81	19 … 20

For the flow rate Q = 29 m^3/h and at water temperature T = 80 ^oC one obtains Re_{nom}=700000.

3. AN APROXIMATION OF EXPERIMENTAL DATA

The coefficient of linear resistances λ for turbulent water flow one may define by the formula by R. Mises:

$$\lambda = 0,0096 + \sqrt{\frac{\chi}{d}} + \frac{1,7}{\sqrt{\mathrm{Re}}}$$

where:

χ – coefficient of wall roughness.

On this basis one can search functional relationship: a = f (Re_{nom}) in the form:

$$a = \frac{A}{\sqrt{\mathrm{Re}_{nom}}} + B$$

where coefficients **A** and **B** may be determined based on set of measuring values by means of method of least squares.

Stable laminar flow in round tubing exists for Re < Re_l = 2300÷2400, however a developed turbulent flow is for Re > Re_t = 3000÷10000. values of Reynolds numbers in external gaps of the fuel element Re_z is smaller than Reynolds number in test stand pipes Re_{nom} and their proportion is:

$$\frac{\mathrm{Re}_z}{\mathrm{Re}_{nom}} = \frac{d_{hz}}{d_{hnom}} \cdot \frac{F_{nom}}{F_z}$$

which gives a value of $\frac{\mathrm{Re}_{z,MC}}{\mathrm{Re}_{nom}} = 0,111$ for the element MC5 and $\frac{\mathrm{Re}_{z,MR}}{\mathrm{Re}_{nom}} = 0,105$ for the element MR6.

It means that the developed turbulent flow in outer gaps may exist for Re_{nom} > 100 000 which determines the range of approximation as a = f (Re_{nom}). In approximation process a number of points lying explicitly outside the concentration area was not taken into consideration. In Table 2 there is a list of received values for the coefficients **A** and **B.**

Table 2 Values of coefficients for approximation curves $a = \frac{A}{\sqrt{\mathrm{Re}_{nom}}} + B$

Fuel element type	A	B
MC5_D	2359.642	10.558
MC5_1	2017.090	11.078
MR6	2461.751	7.416

The plots of the received dependencies are shown on the background of experimental data in Fig. 6.

From the approximative curves received one may reproduce the experimental runs in the coordinate system Δp = f(Q).

These relationships have the following shape:

$$\Delta p = Q^2 \left[\frac{A_1}{\sqrt{Q}} + B_1 \right]$$

The values of coefficients A_1 and B_1 are presented in Table 3.

Table 3 Coefficient values for approximation curves $\Delta p = Q^2 \left[\frac{A_1}{\sqrt{Q}} + B_1 \right]$

	MC5_D		MC5_1		MR6	
T[°]	A_1	B_1	A_1	B_1	A_1	B_1
20	1.3218E-03	5.1495E-04	1.0499E-03	5.4031E-04	1.2813E-03	3.6169E-04
40	1.0628E-03	5.1193E-04	8.4413E-04	5.3714E-04	1.0302E-03	3.5956E-04
60	8.9452E-04	5.0727E-04	7.1046E-04	5.3226E-04	8.6708E-04	3.5630E-04
80	7.766E-04	5.0134E-04	6.1687E-04	5.2603E-04	7.5285E-04	3.5213E-04

The plots of the relationships received are shown on the background of experimental data in Fig. 4.

4. DIFFERENCES BETWEEN DOWN-FLOW AND UP-FLOW PRESSURE DROP

The down-flow and up-flow pressure drops are shown in: Fig. 7 – for MC5 and Fig. 8 – for MR6 fuel assemblies.

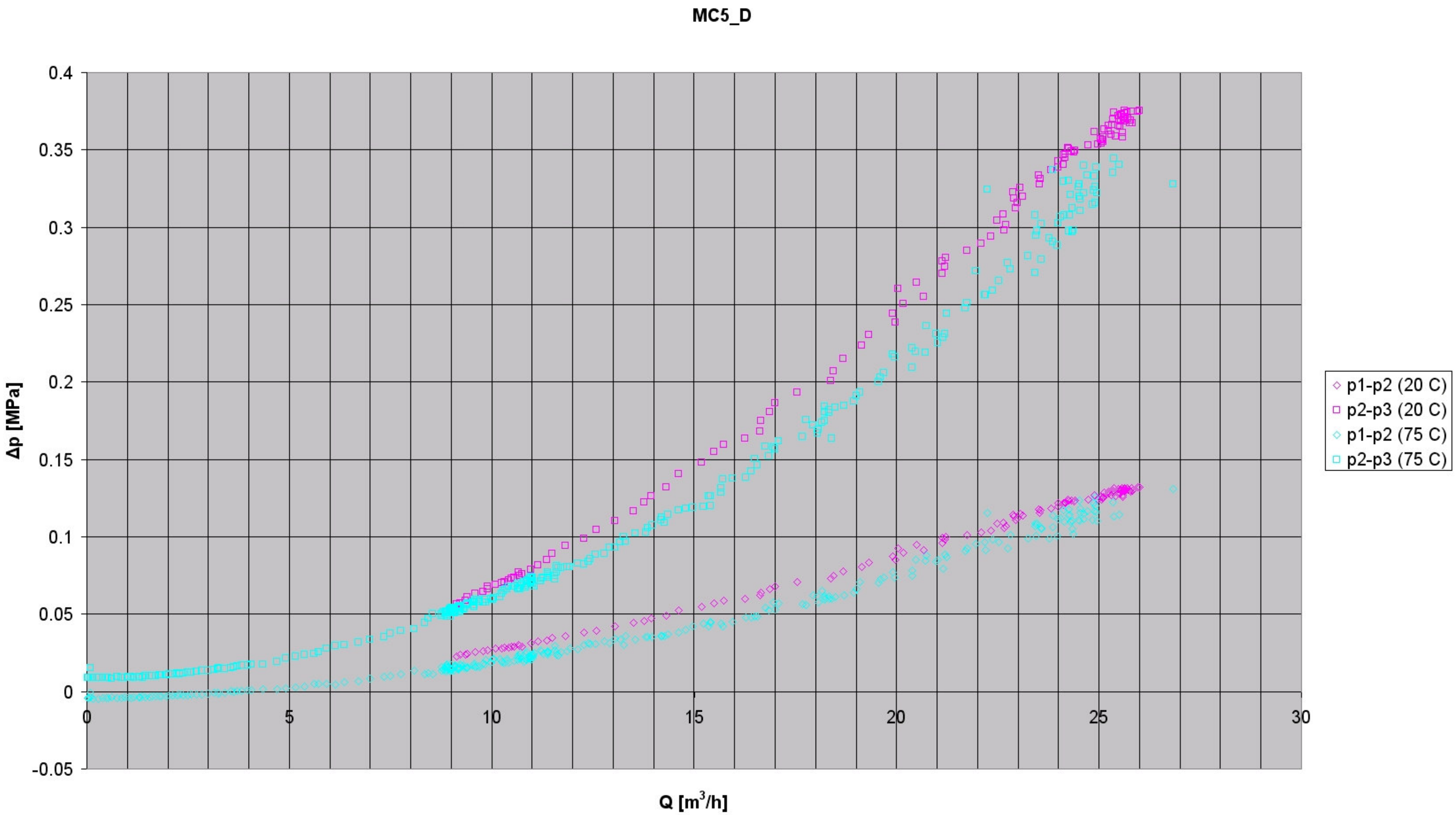

Fig. 7. Comparison of up-flow and down-flow pressure drop for MC5 FA

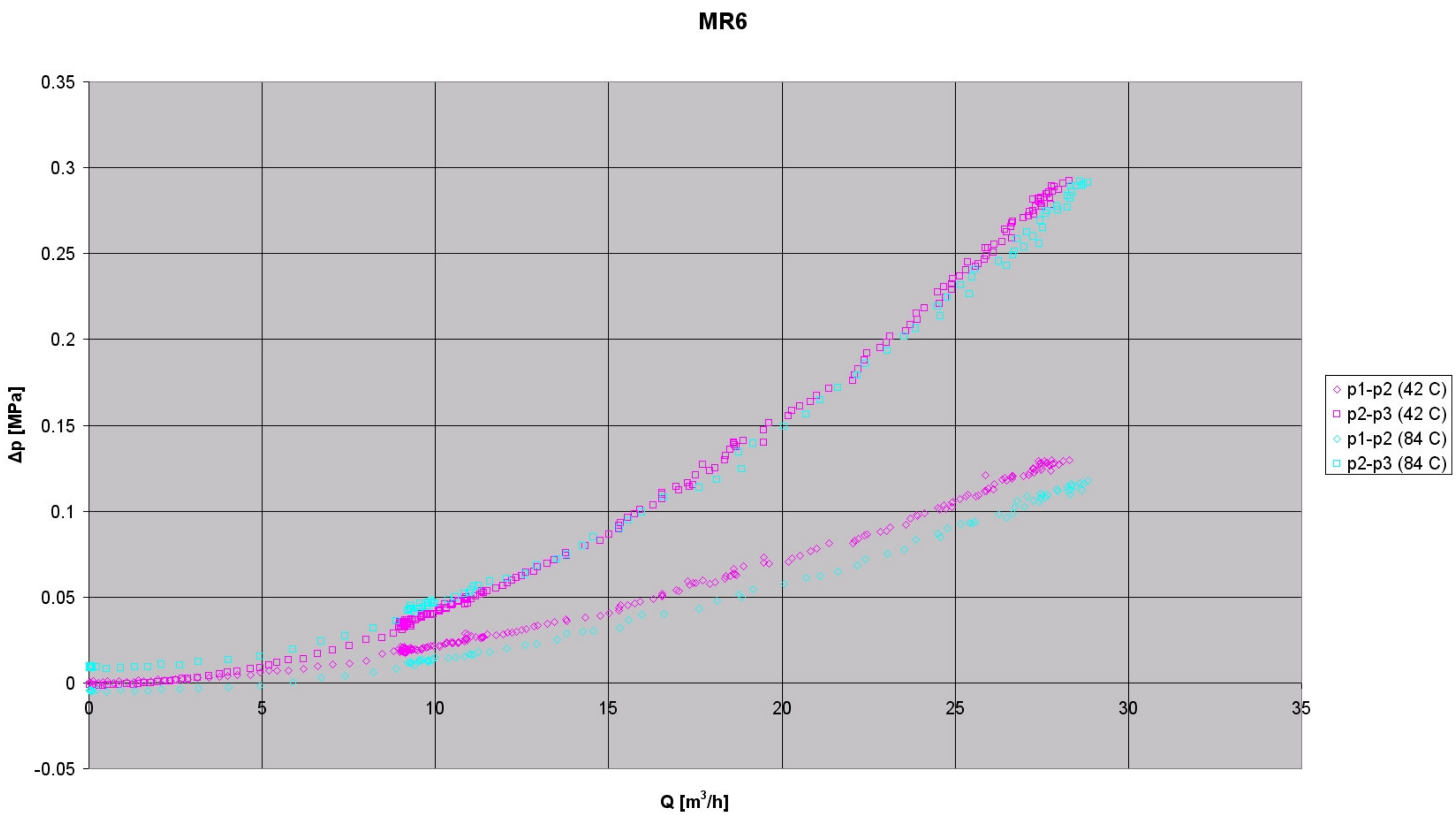

Fig. 8. Comparison of up-flow and down-flow pressure drop for MR6 FA

Table 4 contains values of corresponding areas of flow cross-sections and the flow coolant velocities for both types of fuel elements.

Table 4. Areas of flow cross-sections and coolant flow velocities for Q=25 m^3/h – comparison of MC5 and MR6 fuel elements

Type of fuel element	MC5	MR6
Area of inner gaps [mm^2]	724	1005
Velocity in the inner gaps [m/s]	9.25	6.78
Area of outer gaps [mm^2]	1361	1496
Velocity in the outer gaps [m/s]	5.10	4.64
(p2-p3)/(p1-p2)	3.00	2.24

5. COMPARISON WITH PREVIOUSLY MEASURED DATA FOR MR6 FA

Fuel element hydraulic characteristic was obtained on the out-of reactor test stand in 2002 [2] for the MR6-540 fuel element. In Fig. 9 is shown a comparison of the measurement results from 2002 and data points obtained currently. A bit higher pressure drop on the MR6-540 from 2002 is probably caused by a bigger cladding surface roughness than for currently used MR6-430 FA.

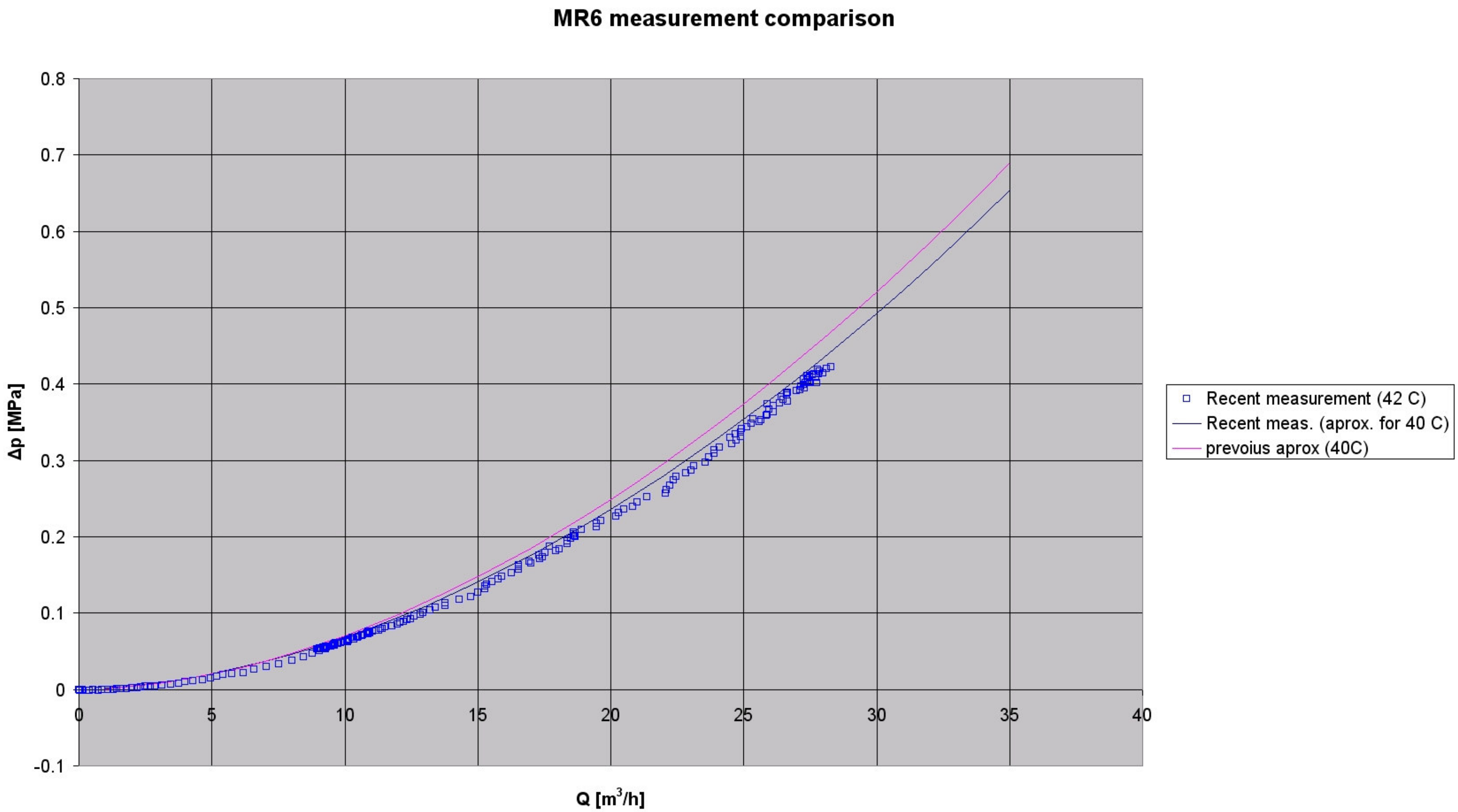

Fig. 9. Comparison between present and previous measurement for MR6 FA

6. MEASURING ERRORS

The basic measurements errors are as follows (based on fabricators data):

- Measurements of coolant flow rate: an ultrasonic flowmeter made by KROHNE of the measuring range: 0.5-35 m^3/h

  Measuring error within the range 1-35 m^3/h: SQ = ±0.5% = ±0.175 m^3/h
- Measurement of pressure: APLISENS pressure sensors of AS type of measuring range 0-2.5 MPa.

  Measuring error: $\delta p = \pm 0.4\% = \pm 0.01$ MPa

  Since there are analyzed relations containing the pressure differences Δp, hence:

  $\delta(\Delta p) = 2\ \delta p = \pm 0.02$ MPa
- Temperature measurement: thermocouple NiCr-NiAl of the type TP-203K-1b-800-5.0 with TCD transmitters of measuring range 0-150°C fabricated by CZAKA company.

  Measuring error: $\delta T \le 0.1$°C.

Since in the analyzed dependences the temperature affects only the value of water kinematic viscosity and density the changes of which in δT interval are negligible hence the error associated with δT was ignored.

However, it is worth mentioning that the temperature measuring accuracy significantly depends on the correctness of thermocouple fitting correctness (an active tip of the thermocouple should be fixed near the axle of pipe). Errors of temperature measuring to be arisen from incorrect fitting are difficult for quantitative estimation. The data presented in co-ordinate system Δp=f (Q) are loaded with basic errors δ(Δp) and SQ which is shown in Fig. 4.

The errors of data points in the functional graph a=f(Re) one can calculate from the following relations:

$$\delta(\mathrm{Re}) = \left|\frac{\partial \mathrm{Re}}{\partial Q}\right| \delta Q = \mathrm{Re}\frac{\delta Q}{Q}$$

$$\delta(a) = \left|\frac{\partial a}{\partial Q}\right| \delta Q + \left|\frac{\partial a}{\partial p}\right| \delta p = a\left[\frac{\delta Q}{Q} + \frac{\delta p}{p}\right]$$

Thus the errors differ for separate points on the graph. In Fig. 5 are shown the errors for two selected points.

Decisive contribution in the notified errors has the pressure measuring error. However, it is worth mentioning that the substantial errors are arising during measurements of quickly changeable coolant flow rate. They are not resulted from the static error associated with flow measuring but they are caused by signal delay due to flow meter response time.

7. CONCLUSIONS

The data acquired from the performed measurements point out that the coefficient of hydraulic resistance for the CERCA MC5 fuel elements exceeds by around 30% the resistance coefficient for the Russian MR6 fuel element. Such a result is mainly caused by lesser cross-sections for coolant flow in the MC5 fuel element in comparison to relevant MR6 fuel element cross-sections (see Table 4). Decrease in MC5 flow cross-sections is caused by two reasons:

- The MC5 fuel element contains only 5 five tubes and therefore it has one flow gap (internal) lesser cross-section;
- All areas of cross-section gaps in MC5 fuel element are a bit reduced by presence of quite massive "stiffeners" (linking bent fuel plates).

As follows from Fig.2 the possibility to achieving at the "cold" state (T-20°C) the flow rate on the level of 29-30 m^3/h through the channel containing the MR6 fuel element should enable to provide the flow rate on the level of 25.5-26.5 m^3/h. Such level of coolant flow rate through the MC5 fuel element should not be exceeded because of too high coolant velocities in the inner gaps.

Not large divergence between the approximation curves of dummy Fuel Element MC5_D and Fuel Element MC5_1 plausibly arises from the fact that the number of conducted measurements for MC5_1 fuel element was substantially smaller then the relevant number for the Dummy Fuel Element MC5_D. It is seen that for high value of Re (i.e., for large flows and high temperatures) the curves are convergent.

8. REFERENCES

[1] „Charakterystyka hydrauliczna kanału paliwowego reaktora MARIA", W. Bykowski, Raport IEA-88/A, Świerk 2002