Investigation and Control of a Regional Steam-Distribution Network under Two-phase Flow Conditions

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Abstract: Measurement and simulation techniques have been developed for a two-phase flow to quantify and qualify a steam network and to determine the flow regime in the network. The development of these techniques makes it possible to create an intelligent monitoring system, which ensures that:

- By the execution of the computational model the different states of the network can be simulated;
- By using the principal of the local dynamic pressure measurement the distribution of the velocity in the cross-section of the pipes near the measurement points can be determined;
- The mass transfer in the condense vessels can be determined in the backbone pipes;
- By using mobile communication the measured data can be transferred immediately to the monitoring system; and
- Algorithms and formulas can be created to determine the quality of the two-phase flow.

Keywords: two-phase flow, identification, modelling, mass transfer network

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1. Introduction

The basis of the research is a 13 km long citywide steam network with pipe diameters between DN50 and DN450. The network distributes approximately 130 thousand tonnes of steam to different parts of the city [1]. To reduce the loss of energy the measurement of the losses and the determination of their spatial and temporal distribution is required, thus suggestions can be made for a more energy efficient operation of the network [2]. The monitoring system installed on the steam network is shown in Figure 1.

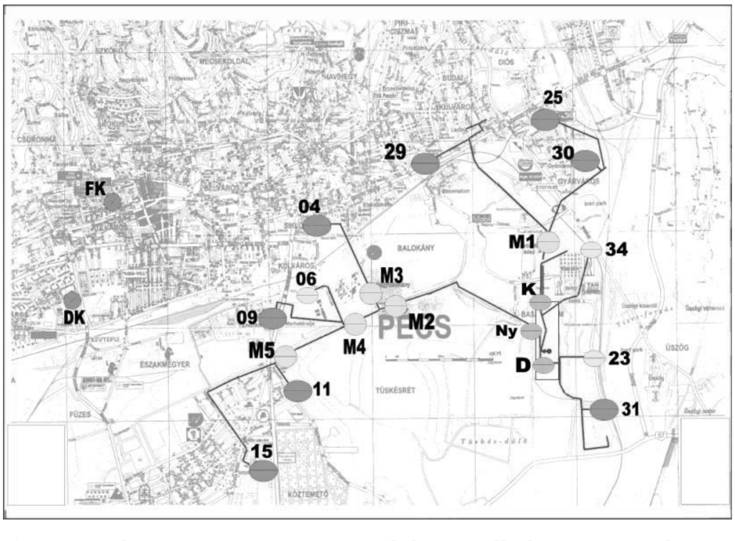

Figure 1. The monitoring system and the installed measuring devices

After the preliminary studies of the steam network it became obvious that some active experiments and measurements must be performed to develop a reliable simulation model for the flow and heat characteristics [3,4,5]. To perform these measurements some special pressure sensors (flow sensors) had to be designed, manufactured and installed. The main reason for the special sensors is that during condensation, the development of the two-phase flow the fluid phase aggregates at the bottom of the pipe and the flow pattern is dominated by this layered flow pattern [6]. The other, basic task for the measurements was to determine and record the topology of the network and to identify sources, passive elements, junctions and the number of consumer points. A geographic information system provides the basis for this survey of a citywide mass and energy network and for the modelling and simulation of the network [7,8,9].

2. The Reasons Behind the Development of the Intelligent Monitoring System

The identification measurements of the steam network indicated a two-phase flow (wet steam) under working conditions.

Furthermore in a reduced operating mode of the distribution steam network the output of the power plant and the measured consumption of the consumers showed a large difference, which indicated the limitations of the current monitoring system, the lack of the measurements of the condensation and the inaccuracy of the measurements of the steam flow. These reasons justified the development of a new, intelligent monitoring system using an expert system software.

The following tasks have been performed in the research:

- the geometry, topology and the data corresponding to the junctions and branches of the network have been recorded, visualised and archived;
- tracing and characterization of the two-phase flow and condensation;
- determination of material properties (thickness of the film, thermal conductivity, heat transfer coefficient, shear stress etc.), properties of the state of operation (velocity-distribution, vapour/liquid volume fraction, critical velocity of steam, etc.), state of flow (layered, annular, spray);
- development of evaluation methods for the signals of the special sensors (volume flow meter operating as a condenser , flow meter based on dynamic pressure measurement, mass flow meter based on an acoustic approach).

The most difficult task was the reliable determination of mass flow and the water content of the mixture. A sensor, based on a method similar to the theory of a classical Pitot-pipe, has been developed, to be able to trace a two-phase, stratified flow. These custom designed sensors had been built into the pipes (see Figure 2).

3. Measurement and Calculation Method for the Characterization of a Two-Phase Flow

The calculation method and formulas developed for the characterisation of a two-phase, stratified flow will be presented for a branch which is instrumented with classical and special measurement sensors as shown in Figure 3.

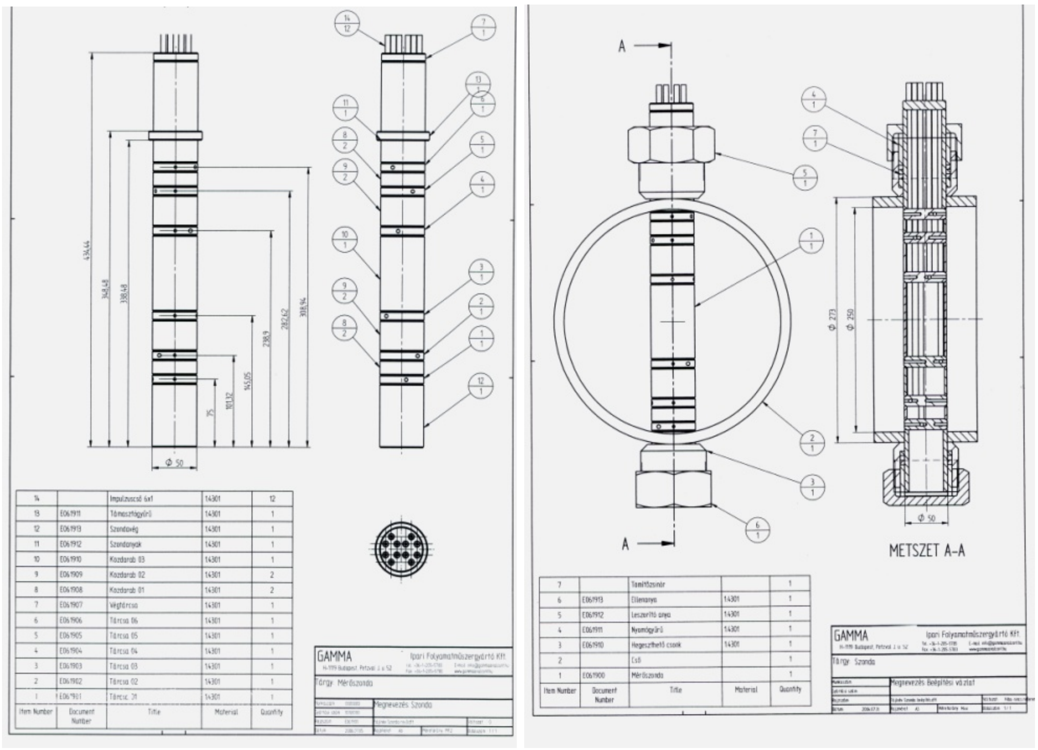

Figure 2. The design and building instructions of the special flow sensors

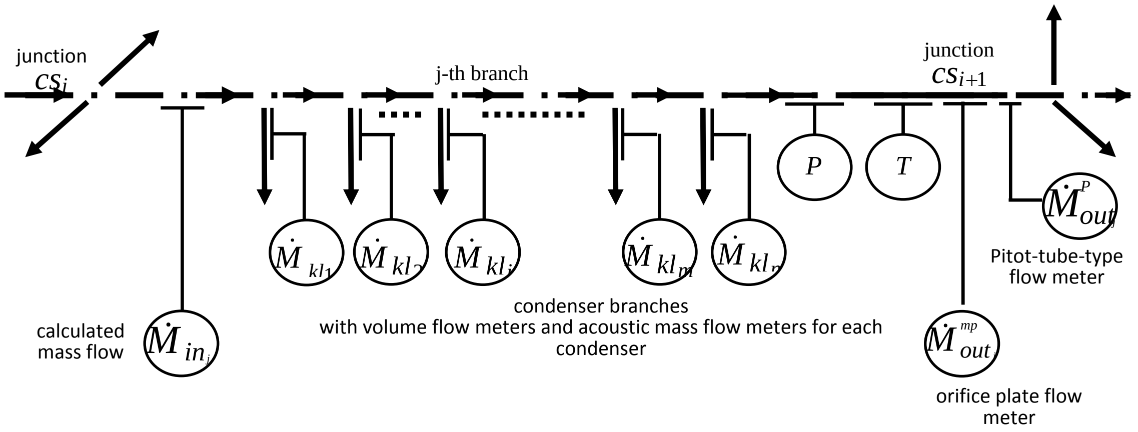

Figure 3. Placement of the measurement sensors for the intelligent monitoring system

The sum of the average mass flow, which is measured using acoustic sensors in branch *j*. between junctions Cs_i and Cs_{i+1} is:

$$\dot{M}_{kl} = \sum_{k=1}^{n} \dot{M}_{kl_k} \tag{1}$$

The mass flow $\dot{M}_{in_j}$ of branch *j* is the mass flow calculated from the sum of entering and leaving mass flow at junction Cs_i. Starting from the source towards the consumption points and moving along all branches of the network the measured mass flow of the segments – considering the reliability of the density of the super heated vapour - can always be regarded as correct in the calculation of the total mass balance.

In order to obtain the correct mass balance, the required density and the outward mass flow, the flow regime can be refined by Pitot-pipe type sensors besides (or instead of) the orifice plate flow meter after the last condenser in the pipe segment. The orifice plate alone cannot provide accurate measurements since the two phases flow separately with different velocities.

The measured values of the orifice plate flow meters – assuming saturated dry vapour at the given pressure and temperature – is $\dot{M}_{out}^{mp}$. The difference between the inward mass flow $\dot{M}_{in}$ decreased by the sum of the mass flow of the condensate $(\dot{M}_{kl} = \sum_{i=1}^{n} \dot{M}_{kl_i})$ and the measured mass flow $\dot{M}_{out}^{mp}$ results in the following mass flow difference:

$$\left(\dot{M}_{in} - \dot{M}_{kl}\right) - \dot{M}_{out}^{mp} = \dot{M}_e \qquad (2)$$

which can be regarded as the consequence of the density variations due to condensation, and due to the lack of density correction (the requirements of the orifice plate measuring are not satisfied) . The correctional multiplier of the orifice plate measurement is given by the following formula:

$$k_{mp} = \frac{\dot{M}_{out}^{mp} + \dot{M}_e}{\dot{M}_{out}^{mp}} \qquad (3)$$

Since the mass flow is proportional with the square root of the average density $\dot{\rho}_k$ of the flowing medium, the relation between the real and the uncorrected density – assumed during the orifice plate-based measuring – can be given as the square of the above correctional multiplier.

For the average density of the flow, the following equation holds:

$$\dot{\rho}_k = \frac{\dot{M}}{\dot{V}} = \dot{\varepsilon}\ \ \rho_g + (1-\dot{\varepsilon})\rho_f \qquad (4)$$

where $\dot{\varepsilon}$, and $(1-\dot{\varepsilon})$- are the volume flow fractions of the vapour and the liquid; ρ_g, ρ_f, $\dot{\rho}_k$ - are the density of the vapour, the liquid, and the mixture [*kg/m*^{3}]; $\dot{M}$ - is the mass flow of the two-phase flow [*kg/s*]; $\dot{V}$ - is the volume flow of the two-phase flow [*m*^{3}*/s*].

In view of the density of the saturated dry vapour and saturated liquid at the measured pressure *p* and temperature *T* with the aid of the above correctional multiplier and applying equation (4) the volume flow fractions can be calculated as:

$$\dot{\varepsilon}\ \rho_g + (1-\dot{\varepsilon})\ \rho_f = (k_{mp})^2\ \rho_g = \dot{\rho}_k \qquad (5)$$

The mass flow $\dot{M}_{ki}$ leaving the branch can be regarded as the measured value of the orifice plate flow meter corrected by the density correction described above (the corrected value must be equal to the inflow decreased by the sum of condensate flows):

$$\dot{M}_{out} = k_{mp}\dot{M}_{out}^{mp} = \dot{M}_{in} - \dot{M}_{kl} \qquad (6)$$

In view of the cross sectional area A_c of the pipe at the measurement point, and the density $\dot{\rho}_k$ calculated by equation (5), the average velocity of the mixture can be written as:

$$u_k = \frac{\dot{M}_{out}}{\dot{\rho}_k A_c} \qquad (7)$$

The Pitot-pipe based measurements carried out in certain branches of the network justified the assumptions that the liquid and vapour phases are separated in the flow and there are significant velocity differences, and under certain operational circumstances a significant portion of the pipe is filled by liquid. The volume occupation of the phases flowing at different velocities cannot be described by the following volume flow fractions:

$$\dot{\varepsilon} = \frac{\dot{V}_g}{\dot{V}_g + \dot{V}_f} = \frac{\dot{V}_g}{\dot{V}};$$

$$1-\dot{\varepsilon} = \frac{\dot{V}_f}{\dot{V}_g + \dot{V}_f} = \frac{\dot{V}_f}{\dot{V}} \qquad (8)$$

where $\dot{V}_g$ ill. $\dot{V}_f$ - are the volume flow of the vapour and of the liquid [*m*^{3}*/s*].

The schematics of the location of the condensate at the measurement points in the horizontal pipe can be seen in Figure 4.

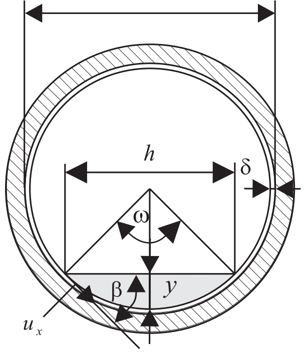

Figure 4. Location of the condensate in horizontal pipe

The local velocities – derived from the dynamic pressures measured at the given points (specified by the corresponding standard) of the measuring section – can be calculated by the following formula:

$$u_{g_i} = \sqrt{\frac{2\,p_{din\,i}}{\rho_g}}\ ;$$

$$p_{din} = p_{ö} - p_{st} \qquad (9)$$

where u_{g_i} - is the local velocity of the flowing mixture at the *i*-th standard location [*m/s*]; p_{din_i} - is the local dynamic pressure of the flowing mixture [*Pa*]; p_{st} - is the local static pressure of the flowing mixture [*Pa*].

The average axial velocity of the steam can be calculated from the local velocities corresponding to the partial cross sections of equal area as follows:

$$u_g = \frac{\sum_{i=1}^{m} u_{g_i}}{m}\ ;\ \mathrm{m}=3,4,5,6 \qquad (10)$$

where u_g - is the average of the *m* local velocities *[m/s]*.

The volume flow $\dot{V}$ of the mixture can be calculated as the quotient of the mass flow $\dot{M}_{out}$ calculated (measured and corrected if needed) by equation (6) and the average density $\dot{\rho}_k$ obtained from equation (5). The volume flow of the phases can be calculated by multiplying the above volume flow by the volume flow fractions of the phases given by equation (8) as follows:

$$\dot{V}_f = (1-\dot{\varepsilon})\dot{V}\ ;$$

$$\dot{V}_g = \dot{\varepsilon}\dot{V} \qquad (11)$$

The mass flows in view of the volume flows and densities of the phases are:

$$\dot{M}_f = \dot{V}_f \rho_f\ ;\quad \dot{M}_g = \dot{V}_g \rho_g\ ;$$

$$\dot{M} = \dot{M}_f + \dot{M}_g \qquad (12)$$

where $\dot{M}_f$, $\dot{M}_g$ - are the mass flow of the liquid, the vapour *[kg/s]*.

The mass flow of the steam $\dot{M}_g$ calculated from the mass flow $\dot{M}_{out}$ leaving the branch and from equations (11) and (12) must not be larger than the mass flow obtained from measurement data - based on dynamic pressure measurement by a special flow meter - given as follows ($\dot{M}_{out} = \dot{M}$):

$$\dot{M}_{g_m} = u_g \left(\frac{m}{6} A_c - \frac{1}{2} A_F \right) \rho_g \le \dot{M}_g \qquad (13)$$

where A_c - is the total cross section of the pipe segment *[m²]*; A_F - is the cross sectional area corresponding to the condensate film *[m²]*; $\dot{M}_{g_m}$ - is the maximum mass flow of the steam calculated from the averaging of measurement data of a satisfactory number of measurement points *[kg/s]*.

The average velocity u_k can be checked in view of the mass flow and density of the phases according to equation (7):

$$u_k = \frac{\dot{M}_g}{\rho_g A_c} + \frac{\dot{M}_f}{\rho_f A_c} \qquad (14)$$

The cross sectional area of the vapour at the location of the special flow meter can be obtained by using the calculated average velocity u_g from equation (10) and the mass flow $\dot{V}_g$ from equation (11):

$$A_g = \frac{\dot{V}_g}{u_g} \qquad (15)$$

The cross sectional area A_f corresponding to the liquid phase is:

$$A_f = A_c - A_g \qquad (16)$$

The volume fractions according to the above calculations corresponding to the volume of a unit length pipe can be calculated as:

$$\varepsilon = \frac{A_g \cdot 1}{(A_g + A_f)1} = \frac{A_g}{A_c}\ ;$$

$$1-\varepsilon = \frac{A_f}{A_g + A_f} = \frac{A_f}{A_c} \qquad (17)$$

where ε and $(1-\varepsilon)$ - are the volume fraction of the vapour and the liquid.

The mass flow fractions can be described by equation (12):

$$\dot{x} = \frac{\dot{M}_g}{\dot{M}_g + \dot{M}_f} = \frac{\dot{M}_g}{\dot{M}}\ ;$$

$$1-\dot{x} = \frac{\dot{M}_f}{\dot{M}_g + \dot{M}_f} = \frac{\dot{M}_f}{\dot{M}} \qquad (18)$$

where $\dot{x}$, and $(1-\dot{x})$ - are the mass flow fraction of the vapour and liquid phases.

The average velocity u_f of the stratified flow can be obtained by calculating the cross sectional area A_f of the liquid at the special flow meters by equation (16) and in view of the volume flow $\dot{V}_f$ of the liquid from equation (11) as follows:

$$u_f = \frac{\dot{V}_f}{A_f} \qquad (19)$$

4. Processing and Evaluation of the Measurement Results Assuming "Slip Model"

It can be stated in view of the flow measurements carried out at the sites of the major consumers that in the case of the steam network operating at low velocities and high hydraulic resistances, the main flow regime is the stratified flow. In order to describe the separate flows of the two phases, the volume occupied by both phases and the measurement based value of the volume fractions ε, and (1-ε) have to be known.

Let us follow the equations of the preceding section. Let's start from the data – obtained under the assumption of the "homogenous model" – and from the values of the average densities $\dot{\rho}_k$, the volume flow fractions $\dot{\varepsilon}$, the average velocities u_k, and $\dot{M}_{kor}^{mp}$ measured by the orifice plate and corrected by the correctional multiplier k_{mp} (in the case of branches lacking orifice plate flow peters, the measured mass flows can be substituted by the mass flow calculated from the mass balance, the inward mass flow $\dot{M}_{in}$ decreased by the total condensate flow $\dot{M}_{kl}$). Based on formula in the case of homogenous model, equation (9) during the substitutions in the the average density $\dot{\rho}_k$ and the dynamic pressure p_{din_i} - measured by the Pitot-pipe - had been applied. Under the assumption of the "slip model", the same is carried out by applying the vapour density ρ_g.

The results of the velocity measurement series are summarized in Table 1. The location of the condensate in the horizontal pipe can be deduced from the cross sectional area values A_f of the liquid phase, which can be found in the table. The area of the part of the cross section occupied by the liquid can be obtained from the following formula:

$$A_{sz} = \frac{1}{2} r^2 \left(\frac{\pi}{180^\circ} \omega - \sin \omega \right) \qquad (20)$$

where A_{sz} - is the area of the circle section *[m²]*; r - is the inner radius of the pipe decreased by the average thickness δ_r of the condensate film *[m]*; ω - is the central angle denoted in Figure 4.

The velocity distribution is shown in Figure 5. The increase of the average liquid content results in the increase of dynamic pressures at the inner measuring points of the cross section (increasing velocity assuming dry vapour density), and decreasing velocity towards the wall of the pipe and the surface of the liquid.

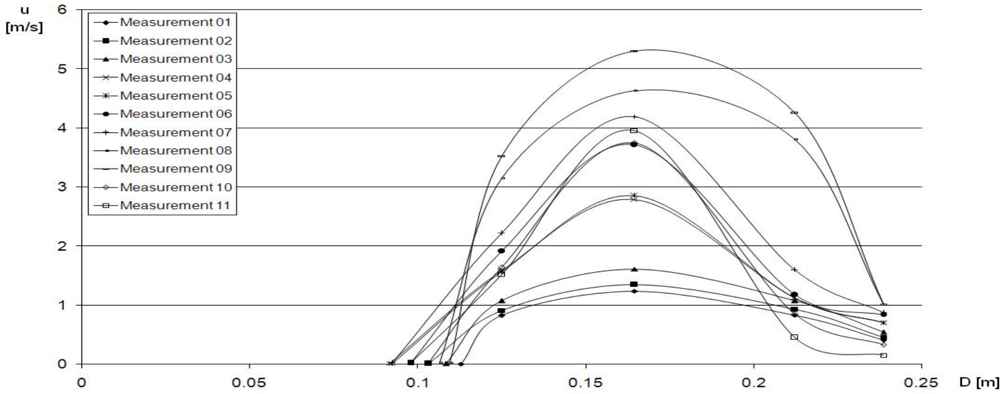

Figure 5. Velocity distribution of the two-phase

Table 1. The calculated characteristic values of the two-phase flow assuming "slip model"

Ms. ser.	$\dot{M}^{mp}$ $\left[\frac{t}{h}\right]$	$\dot{M}^{mp}_{kor}$ $\left[\frac{t}{h}\right]$	$\dot{\rho}_k$ $\left[\frac{kg}{m^3}\right]$	u_k $\left[\frac{m}{s}\right]$	$\dot{M}$ $\left[\frac{t}{h}\right]$	$\dot{\varepsilon}$ $[\%]$	$1-\dot{\varepsilon}$ $[\%]$	$\dot{V}$ $\left[\frac{m^3}{h}\right]$	$\dot{V}_g$ $\left[\frac{m^3}{h}\right]$	$\dot{V}_f$ $\left[\frac{m^3}{h}\right]$	$\dot{M}_g$ $\left[\frac{t}{h}\right]$	$\dot{M}_f$ $\left[\frac{t}{h}\right]$	$\dot{x}$ $[\%]$	$1-\dot{x}$ $[\%]$	u_k (1.) $\left[\frac{m}{s}\right]$	u_{g3} $\left[\frac{m}{s}\right]$
1.	0,605	0,813	9,989	0,462	0,816	99,49	0,51	81,6886	81,272	0,4166	0,4495	0,368	54,98	45,02	0,4623	0,8233
2.	0,82	1,102	9,989	0,5593	0,988	99,49	0,51	98,9088	98,4044	0,5044	0,54427	0,44565	54,98	45,02	0,5597	0,9102
3.	0,86	1,1588	9,989	0,636	1,123	99,49	0,51	112,4237	111,8503	0,5734	0,61864	0,50655	54,98	45,02	0,6362	1,0751
4.	1,36	1,83	9,989	1,028	1,815	99,49	0,51	181,7	180,7732	0,9267	0,99986	0,81869	54,98	45,02	1,0282	1,5374
5.	1,36	1,83	9,989	1,0357	1,828	99,49	0,51	183,0	182,067	0,933	1,00701	0,82427	54,98	45,02	1,0355	1,5575
6.	1,56	2,097	9,989	1,2103	2,137	99,49	0,51	213,9351	212,844	1,0911	1,17724	0,96393	54,98	45,02	1,2106	1,9082
7.	1,9	2,553	9,989	1,47	2,596	99,49	0,51	259,846	258,521	1,325	1,42988	1,17077	54,98	45,02	1,4703	2,2172
8.	2,41	3,239	9,989	1,8832	3,325	99,49	0,51	332,896	331,198	1,698	1,83186	1,49992	54,98	45,02	1,8837	3,1442
9.	2,6	3,4944	9,989	2,053	3,625	99,49	0,51	362,899	361,048	1,8508	1,99696	1,63511	54,98	45,02	2,0536	3,5193
10.	1,36	1,934	11,186	1,015	2,007	99,356	0,644	179,4205	178,265	1,1555	0,986	1,02082	49,13	50,87	1,0153	1,6402
11.	1,36	2,0686	12,796	0,972	2,198	99,173	0,827	171,7778	170,3572	1,4206	0,94225	1,25506	42,88	57,12	0,9720	1,5185

Ms. ser.	$\dot{M}_{g3}$ $\left[\frac{t}{h}\right]$	u_{g4} $\left[\frac{m}{s}\right]$	$\dot{M}_{g4}$ $\left[\frac{t}{h}\right]$	$\dot{M}_g - \dot{M}_{g3}$ $\left[\frac{t}{h}\right]$	A_g $[m^2]$	A_f $[m^2]$	ε $[\%]$	$1-\varepsilon$ $[\%]$	u_f $\left[\frac{m}{s}\right]$	$A_{g1.2.3}$ $[m^2]$	$\varepsilon_{1.2.3.}$ $[\%]$	$1-\varepsilon_{1.2.3.}$ $[\%]$	$u_{g1.2.3.}$ $\left[\frac{m}{s}\right]$	$u_{k1.2.3.}$ $\left[\frac{m}{s}\right]$	$u_{k4.5.6.}$ $\left[\frac{m}{s}\right]$	u_k (2.) $\left[\frac{m}{s}\right]$
1.	0,4015	0,7747	0,5040	0,4145	0,02742	0,02166	55,8680	44,1320	0,00534	0,0029	11,9562	88,0438	0,8223	0,1030	0,8214	0,4622
2.	0,4439	0,9058	0,5892	0,1004	0,03003	0,01906	61,1772	38,8228	0,00735	0,0055	22,5769	77,4232	0,9102	0,2112	0,9083	0,5597
3.	0,5243	1,0399	0,6765	0,0944	0,02890	0,02019	58,8712	41,1288	0,00789	0,0044	17,9641	82,0359	1,0751	0,1996	1,0728	0,6362
4.	0,7497	1,7590	1,1443	0,2502	0,03266	0,01642	66,5401	33,4599	0,01567	0,0082	33,3043	66,6557	1,5374	0,5225	1,5340	1,0282
5.	0,7595	1,7742	1,1542	0,2475	0,03247	0,01662	66,1487	33,8513	0,01560	0,0080	32,5207	67,4793	1,5575	0,5170	1,5541	1,0356
6.	0,9305	2,1034	1,3683	0,2467	0,03098	0,01810	63,1198	36,8802	0,01674	0,0065	26,4627	73,5373	1,9082	0,5173	1,9041	1,2107
7.	1,012	2,4145	1,5707	0,3487	0,03239	0,01670	65,9799	34,0201	0,02204	0,0079	32,1837	67,8163	2,2172	0,7285	2,2124	1,4705
8.	1,5332	3,2475	2,1126	0,2986	0,02926	0,01983	59,6075	40,3925	0,02379	0,0048	19,4370	80,5630	3,1442	0,6303	3,1374	1,8839
9.	1,7161	3,5903	2,3356	0,2808	0,02850	0,02059	58,0546	41,9454	0,02497	0,0040	16,3284	83,6716	3,5193	0,5955	3,5116	2,0536
10.	0,7998	1,9334	1,2578	0,1862	0,03019	0,01890	61,5042	38,4958	0,01696	0,0057	23,2309	76,7691	1,6402	0,3941	1,6366	1,0153
11.	0,7405	2,0666	1,3444	0,2018	0,03116	0,01792	63,4868	36,5132	0,02202	0,0067	27,1968	72,8032	1,5185	0,4290	1,5152	0,9721

5. Conclusions

The requirements of the investigation of the two-phase flow in order to ensure the correct scoring of energy are the following:

- development and operation of special flow meters (Pitot-pipe type, capable of following the local velocity distribution),
- developing of computational methods for the processing and evaluation of the data provided by the above devices,
- calculation methods, in order to obtain information about the flow regime, and for the estimation of the characteristic values of the flow.

The construction and development of the above devices and methods have provided the strategic background for the establishment of an intelligent monitoring and expert system.

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