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APPLICATION OF „GAS-LIFT“ IN NUCLEAR REACTORS IV. GENERATION AND ITS EXPERIMENTAL VALIDATION.

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This work describes the selection of type of a two-phase flow, suitable for intensifying of a natural flow of nuclear reactors with liquid fuel and the description of a „Two-phase flow demonstrator“ used for experimental study of the „gas-lift“ system and its influence on the support of natural convection. The experimental device works with water and the air is used as a gas. There are stated relations for the description of a natural flow in model device and relations for determination of suitable liquid/gas ratio of the gas-lift in the study

Keywords: two-phase flow, experimental device, cooling mixture molten salts

Introduction

There is possible to use a very well known gas-lift for the intensification of natural flow in nuclear reactors.

The information about pumping of the water from mines using the gas come from Chemnitz from the middle of the eighteenth century. It is now used intensively in two forms during crude-oil mining:

a) continual delivery of the gas into the flow.

b) periodical injection of the gas, which is more effective for mining.

It is only possible to use the continual gas delivery method in nuclear reactors. It is possible to use He as a gas. In MSR the gas-lift is suitable for cleaning the fuel-cooling mixture of fluoride salts from gaseous fission products and therefore removing the problems with „Xenon Fission product poisoning“ of classic reactors. There is applicable the bubble mode and the disperse bubble mode that allows larger flow intensification - from the types of the two-phase flow. The other modes like slug mode, churn mode and annular mode are unsuitable for non-homogeneous distribution of the phases.

The bubble mode changes to the disperse bubble mode for the high fluid velocity. There can be up to of-the-order differences between limits of the bubble mode and the slug mode according to different authors (e.g. according to [2] the limit is for v_{gs}=0.61m/s, similarly the switching to disperse flow is for pro v_{ls}=3m/s).

The disperse bubble flow for high fluid velocity is also above other modes. The disperse bubble flow is technically homogeneous, because the bubbles are very small. Unlike in the bubble, slug and churn mode there is no movement acceleration of the gas bubbles and therefore its valid for the disperse bubble mode, that $v_g = v_l$, the gas slip ration $S = v_g/v_l = 1$.

There is a problem in determination of weight flow rates of the fluid and gas [kg/s] W_∞ and W_g to get to the sphere of the disperse bubble flow.

There applies:

$m_l = \rho_l(T_{max})\cdot A_k\cdot v_{sl}$ and $m_g = \rho_g\ (T_g\ )\cdot A_k.v_{sg}$. where the cross-sectional area of the tractive cylinder is $A_k = \pi\cdot D^2/4$, ρ is density, index l is the fluid,g is the gas, m [kg/s] is the weight flow rate.

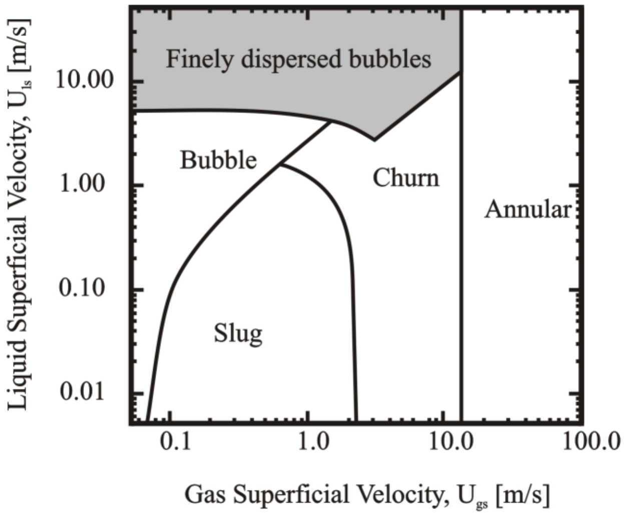

Fig. 1 Map of distribution of the types of a two-phase flow (Taitel) [1]

It is assumed to use water with a in the model. The temperatures and also the volumetric air rate supplied by the compressor are measured. It is necessary to determine the volumetric share of the gas ε_g at the beginning of the tractive cylinder. Because the maps of division of the two-phase flow vary from author to author, it will be necessary to check on the model, that we are in the sphere of the bubble flow in different rates of the supplied air.

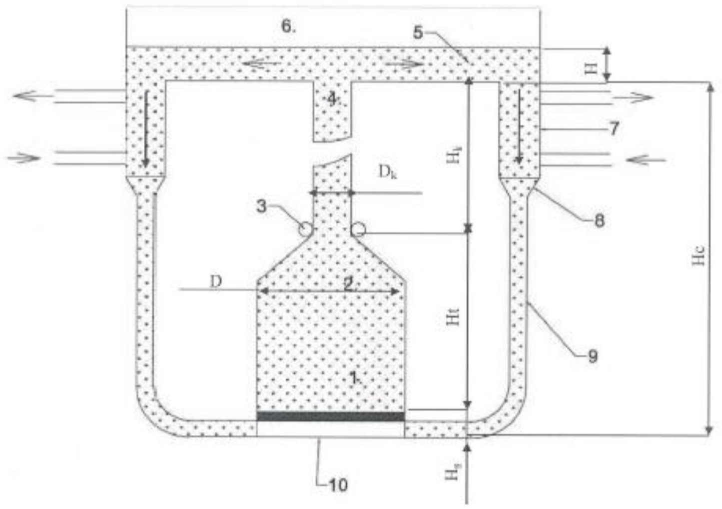

Fig. 2 Simplified scheme of the primary circuit

1. Active zone
2. Crossing to tractive cylinder
3. Gas intake (He) for the gas-lift
4. tractive cylinder
5. Compensator of volume with free surface
6. Area for collected gas
7. Counterflow exchanger
8. Crossing to the cold branch tubing
9. Cold branch
10. Collecting chamber
11. Distribution vents for flowing into the active zone

At first we state a simplified scheme of the primary circuit (fig. 2). We will consider e.g. the integral arrangement in the reactor container of homogeneous MSR-type reactor. The main construction material for a primary circuit of a high-temperature reactor is graphite and its composites. For the operation temperatures up to 7200C Hastelloy N or Monicr Škoda JS.

There were deduced the relations for natural nuclear reactor coolant flowing and reactors with flowing fuel-cooling MSR mixture in the work [6].

2. Demonstrator of the two-phase flow

The experimental device that is in this work signed as the Two-phase flow demonstrator (TFD) is a model device that is used for experimental studies of the gas-lift system and its influence on the natural convection support. There was provided space in the lab L136 at the Department of Power System Engineering, Faculty of Mechanical Engineering, University of West Bohemia in Pilsen. for this purpose.

The device represents a very simplified model of the primary circuit of the reactor with fuel in liquid salts. In the TFD unlike the MSR there is normal water flowing and the supplied gas is air. The measurings in water and air provide series of interesting results and points out the problems that can occur during the construction of the device with flowing liquid salts.

The experimental device consists of the series of construction parts that have been named after the parts of the primary circuit, that they represent. The model of the whole device including the description of its main parts is shown in the figure 3.

There were used two types of the construction material – metal from the carbonaceous steel and perspex. The most parts are welded from the 2mm thick metal plates. The remaining parts, that have to be transparent in order to perform the PIV measurements are made from the 5mm or 10mm thick perspex depending on the strain of the part. The maximum dimensions of the device are 2160 x 1100 x 360 mm (height x length x width).

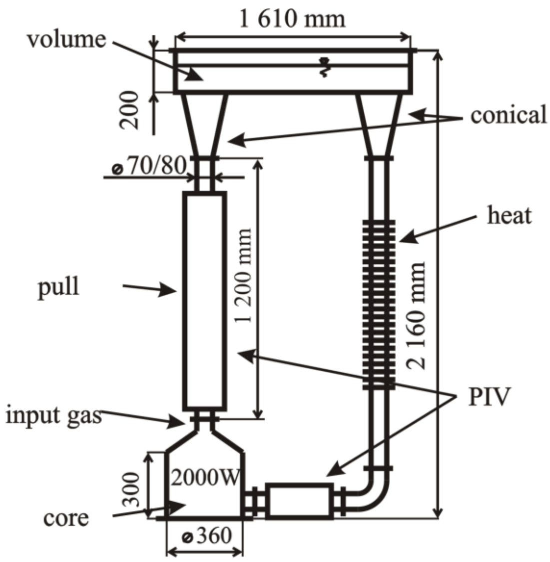

Fig. 3 The model of the two-phase flow demonstrator

The active zone (AZ) is represented here by the cylindrical metal container of 360 mm diameter and height of 300 mm. There is a conic crossing in its upper part and the are of air intake for the gas-lift follows. The heat source in the model AZ secures a 2000 W heating unit that is bolted and correctly sealed to the wall of the container in its bottom part in order not to obstruct the flowing water and therefore not to increase the pressure losses. The bottom of AZ, that has to be removable in order of assembling and potential exchange of the heating unit, is connected with the cylindrical part of AZ using the flange and twelve screws. There is bolted a ball valve for filling and drainage in the bottommost part of the AZ.

Fig. 4 two-phase flow demonstrator

There is welded a short tube of a 70 mm diameter with ten vents for the air intake above the conic crossing. In the wall of the tube there are drilled ten vents and then welded the M12 nuts for these purposes. There is one pressure pipe welded via inserted reduction to every nut, that transfers the compressed air from the compressor to the area of the tractive cylinder intake. One point of the measurements is to determine the influence of the size of supplied air on the water flow rate TFD water loop. Therefore it is essential to change the diameter of individual vents for air intake easily in order to control the size of the created bubbles in the tractive cylinder. There are used changeable brass insets that are situated in the reduction in between the pressure pipe and the tractive cylinder entry for these purposes. The reduction - that is actually a drilled-through screw with one inside and one outside threading – and the changeable brass inset determining the size of the air intake vent are shown in the figure 4. There is a number of the changeable insets with vent diameters of 0,5mm, 1 mm and 2 mm available. In case we don't use the inset in the reduction, the diameter of the entry vent is 7 mm, therefore we have four options of the air intake vent size.

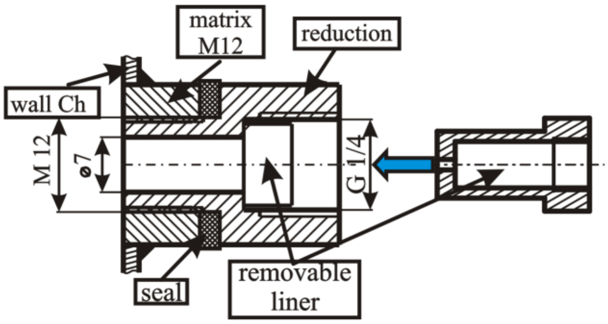

Fig. 5 The reduction with changeable inster

Tractive cylinder is made of the perspex pipe of a circular cross-section with inside diameter of 70 mm and the wall thickness of 5 mm. Its height is 1200 mm. It is connected (using the flange) to a metal pipe with previously mentioned ten vents that are used for the air intake. For reaching the maximum fluid velocity it is necessary to secure:

a) maximum difference of the medium height of the exchanger and the active zone and simultaneously such an exchanger affectivity, that decreases the maximum temperature for ΔT_c for natural flowing. (It hasn‘t been secured during the first measuring and the exchanger has to be adjusted for the next measuring in order to fulfill the condition.)

We obtain this relation for natural heat flowing in the primary circuit - on condition that the temperature changes only in the active zone and the heat exchanger - from the solution of the continuity equation and the Bernoulli’s equation:

$$\tilde{\chi}_{pr} \cdot \frac{W_\infty^2}{2 \cdot \bar{\rho}} - \bar{\rho} \cdot g \cdot \beta \cdot \left(\bar{z}_v - \bar{z}_c \right) \cdot \Delta T_c = 0 \tag{1}$$

Where

W_∞ is the weight flow rate for the balanced flow of the coolant in the zone [kg/s]

g is the gravitational acceleration,

β is the coefficient of the volume expansion

ΔT_c is the thermal heating in the active zone.

$$\tilde{\chi}_{pr} = \frac{\chi_{pr}}{\bar{\bar{A}}^2} \tag{2}$$

$\varkappa_{pr}$ are total hydraulic losses in the primary circuit, $\bar{A}$ is the medium flow cross-section of the circuit.

It applies:

$$\frac{1}{\bar{\bar{A}}} = \frac{-}{L} \int_{x_0}^{x_L} \frac{dx}{\rho(x).A(x)} \tag{3}$$

$$\overline{\rho} = \frac{1}{V} \int_{x_0}^{x_L} \rho(x).A(x).\, dx \tag{4}$$

L is the total circuit length, V is the total volume of the coolant in the circuit.

For ΔTC It applies from elementary balance for: $\Delta T_c = \frac{P}{c_p \cdot W_\infty}$ (5)

P [W] is the total heat output of the zone,

c_p is the thermal capacity of the fuel.

$\bar{z}_v$, $\bar{z}_c$ are the medium heights of position of the exchanger and the active zone in the primary circuit. After the adjustment we obtain:

$$W_\infty = \left[\frac{2 \cdot \bar{\rho}^2 \cdot g \cdot \beta \cdot P}{\tilde{\chi}_{pr} \cdot c_p} \cdot \left(z_v - z_c \right) \right]^{\frac{1}{3}} \tag{6}$$

b) For gas-lift it applies in the tractive cylinder of the diameter $A_K \left[\mathrm{m}^2 \right] = \frac{\pi}{4} \cdot D_K^2$ according to the rule of

$$W_\infty^{gas-lift} = \left(W_{l\infty} + W_g \right) \left[\frac{\mathrm{kg}}{\mathrm{s}} \right] \tag{7}$$

Using $W_\infty^{gas-lift}$ it is necessary to use in general c_p and ρ for a two-phase mixture and simultaneously determine the new losses, because $W_\infty^{gas-lift}$ increases the flow velocity in the whole primary circuit.

The amount of the gas supplied by the m vents into the tractive cylinder of the gas-lift W_g is determined by the following relation from [3]

$$W_g = C_d \cdot \frac{\pi}{4} \cdot d^2 \cdot m \cdot p_1 \cdot \sqrt{\frac{1}{r \cdot T_g} - \left(\frac{2 \cdot \kappa}{\kappa - 1} \right)} \cdot \sqrt{\left(\frac{p_2}{p_1} \right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}}} \tag{8}$$

Where

m	is the number of the vents of the d diameter,
C_d	is the loss coefficient that has to be determined experimentally,
p_1	is the gas pressure in front of the strangling hole,
p_2	is the gas pressure behind the strangling hole
$\kappa = 1{,}66$	for single atomic gases (He, Ar, Kr),
$\kappa = 1{,}4$	for O_2, N_2, CO, air,

Alongside the height of the tractive cylinder is situated a pool of a square cross-section made of perspex with the wall thickness of 5 mm that is necessary for possibility of measuring of the flow using PIV. The pool is during the measurements filled with water and therefore eliminates the influence of different light refraction index in water and on air. The light spreads faster in the air than in the water, while in the water and perspex is the light velocity very similar. It is necessary to create a plane that is perpendicular to the axis of the camera in the crossing between the air and water, if the picture recorded by the camera should correspond with reality. This is secured when the pool is full.

The maximum temperature, during which is the used perspex able of a long-term work, is 60 degrees, which is also the maximum operating temperature of the TFD.

There is a conic metal crossing of 300 mm height attached using the flanges between the tractive cylinder and the volume compensator (VC). It slows down the flow fluently, that also lowers the local pressure losses during the crossing from the tractive cylinder to the volume compensator. The VC is essentially a topless rectangular pool made of perspex with dimensions 1050 x 300 x 200 mm. The water inlet and outlet openings are located at the base. The VC secures for the TFD not only the compensation of water volume changes caused by its temperature, but mainly enables outlet of the gas used for the gas-lift.

There is water from the VC flowing through the conic crossing into the vertical metal pipe of a 70 mm diameter, which provides the function of a heat exchanger. The heat outlet is provided by the forced air convection around the exchanger pipe caused by simple blowing of the air by two ventilators. The remaining parts of the TFD are thermally isolated to prevent from unwanted thermal losses.

There is a metal arch, that turns the flow into a horizontal direction, attached using the flanges in the bottom part. The water then flows through the pipe made of perspex that also contains a perspex pool that enables the PIV measuring. Finally the water returns to the AZ and the cycle repeats.

Because the whole device is relatively large (maximum dimensions: 2160 x 350 x 440 mm) and therefore rather heavy, when filled with water (operating water filling ca. 100 litres), it has to be held by a supporting structure. There have been used square aluminium profiles. They are light and secure sufficient loading capacity and solidity of the structure.

The source of the air for the gas-lift provides the Atmos compressor with the pressure container with capacity of 150 litres. There is an air-pressure-rate regulating valve located behind it.

3. Measuring devices and sensors on the TFD

It is necessary to install some measuring devices and sensors on the TFD to enable studying of the gas-lift and natural flow due to the water heating in the AZ. The water flow rate is measured by the induction flow meter from the lab equipment, that is attached by flanges to a vertical metal pipe under the area of the heat exchanger. The request of the minimum calming length ahead and behind the flow meter given by the manufacturer has been taken into consider during the flow meter assembly. The output of the flow meter is a voltage signal of 0 to 10V, which is transferred to the computer using the A/D converter by National Instruments (NI) and the LabView software.

At the beginning of 2012 there were supplied 3 rotameters of different extents for the air volume flow rate measuring. They were situated next to each other on a simple panel, where it is possible to switch the air flow between the individual devices using the valves. This way we can measure the air flow rate in the extent of 0,1 to 60 1/min. The air flow rate is displayed on the scale and the manufacturer claims ± 5% accuracy, when reading directly. The rotameter is the most suitable option regarding the request of measuring of a small air flow rate and simultaneously significantly large flow rate extents.

The air pressure is measured behind the pressure container outlet of the compressor by a classic analogue pressure gauge with range of 0 to 10 bar, which is a part of the compressor. The measurings have been performed for three different air pressures – 1,5; 3 and 5 bar.

The water temperature is measured using the thermocouple in three different spots for the purposes of natural convection studies. It is at the outlet of the AZ (maximum temperature in the circuit), above the tractive cylinder and behind the heat exchanger (minimum temperature in the circuit). The cold end of the thermocouple is compensated electronically in the convertor for thermocouple from NI. The advantage of the thermocouple is their low price if we don't take into consider the price of the NI hardware and software, which is available at the Department of Power System Engineering. Next advantages of the thermocouple are quick reactions to the temperature changes, easy use, wide extent and a rather good accuracy.

The last and most extensive measuring device is the PIV apparatus, that has been described in a separate chapter. We can watch in detail the flowing in the tractive cylinder using the PIV. The advantage of this method is an exact description of the velocity field in a specific spot and the possibility of an extensive numerical analysis of the results.

4. The principle of the PIV method

Particle Image Velocimetry (PIV) is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow. Two velocity components are measured, but use of a stereoscopic approach permits all three velocity components to be recorded, resulting in instantaneous 3D velocity vectors for the whole area. The use of modern digital cameras and dedicated computing hardware, results in real-time velocity maps.

The measuring apparatus

The cross-section of the fluid, in which there are evaluated the instantaneous velocities, is realized using the laser. The laser beam is shaped to a light sheet using the special optical system. The display of reference particles is recorded by a camera, of which axis is placed perpendicularly to the cross-section level.

The recorded images are divided into smaller square fields that are called „Interrogation Area". In order to measure the flowing velocity, it is necessary to have two images of the interrogated area with exactly defined time interval. The gained images are processed by the software, that uses the mathematical apparatus of a quick Fourier transform and mutual correlation for investigation of an average move of the particles in every interrogated area. The results of the measuring can be very illustratively visualized using the vector field.

There are used the CCD cameras for image recording. The main parameters determining the quality of the camera are speed, sensitivity and resolution. There are used pulse lasers that are able to issue a sufficiently strong radiation, which enables to reach a very short exposition and therefore to capture the most exact images. The essential part of the apparatus is the synchronizer that provides the time synchronization of the camera shutter and the laser pulse. The synchronizer is also able to exactly determine the time interval between the two pulses, which is one of the essential conditions for correct flow velocity determination.

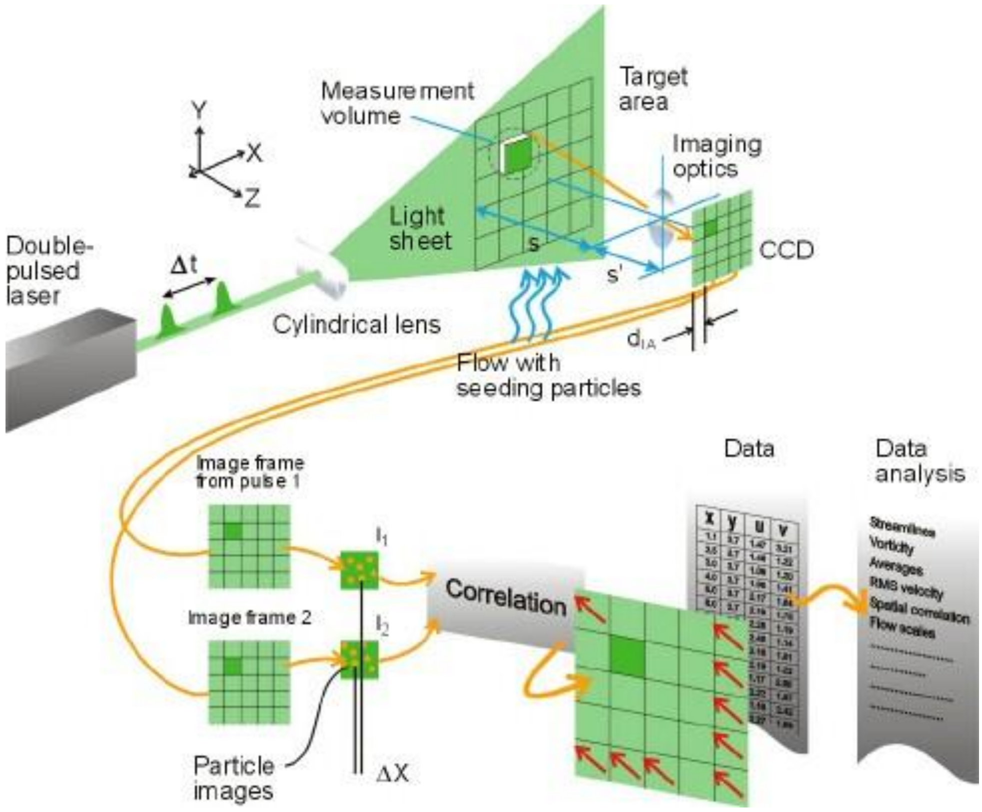

Fig. 6 The scheme of the PIV measuring layout [9]

Verification of the reference particles suitability for the PIV

At first it is essential to choose suitable reference particles for the PIV measuring. For measuring of the natural convection there have been used ball-shaped hollow glass spheres by Dantec Dynamics of average diameter of 10 µm – the range of the diameters is 2 µm to 20 µm. It is possible to verify the suitability of the spheres for given application by these two following relations:

$$t_s \cong d_p^2 \frac{\rho_p}{18.\mu} \tag{9}$$

$$v_s = \left(\frac{g\,.\,d_p^2}{18\,.\,v_f}\right)\left(\frac{\rho_p}{\rho_f} - 1\right) \tag{10}$$

The t_s quantity is the response time of the reference particles, depends on the dimensions and density of the reference particles and on the dynamic viscosity of the measured fluid. It is essential, that the response time of the reference particles is significantly lower than the characteristic time of the PIV measuring, which is the time difference between the two images. The v_s quantity is the velocity of reference particles sedimentation, that depends on the dimensions and density of the reference particles on the kinematic viscosity and density of the measured fluid. It is essential, that the sedimentation velocity is significantly lower than the medium velocity of the measured fluid flow.

The PIV measuring has been performed for two basic options of flowing in the DDP – flowing during the natural convection caused by heating of the water in the AZ and flowing during the forced convection caused by the gas-lift. There were used the hollow glass spheres with density of 1,1 g/cm3 and medium diameter of 10 μm for the PIV measuring on the TFD. The measuring is performed in water whose physical parameters as the density and viscosity are well-known.

It is impossible to use classic reference particles for the PIV measuring in gas-lift where the air bubbles occur, because of the noticeable light reflections on the surface of the bubbles. The solution is in using of the fluorescent particles, that are covered by a thin layer of rhodamine. These modified particles absorb the laser light of wavelength of 532 nm and emit the light of wavelength of ca 580nm. There is an optical filter placed on the camera that records the velocity field. This filter screens out absolute majority of radiation of wavelength lower than 580 nm and thus also the laser radiation. The reflections of the laser beam on the surface of the bubbles are then almost invisible for the camera. The fluorescent particles have the medium dimension of 30 μm and the density of 1,19 g/cm^3.

The following values of response time of the reference particles then come out of the relations (9) and (10):

	Glass spheres	**Fluorescent particles**
vs	$5{,}5.10^{-6}$	6.10^{-5}
ts	$6{,}1.10^{-6}$	$9{,}3.10^{-5}$

Chart 1 Sedimentation velocity and response time of the reference particles

The fluorescent particles are larger and heavier than the glass spheres and therefore they sediment faster and have a longer response time. The minimum velocity in the TFD is in 10-2 orders, which is at least 3 orders more, than the sedimentation velocity. The reference particles are suitable from this point of view. The minimum amount of time between the two camera images during the PIV measuring is in 10-3 sec. Orders, which is again significantly more than the response time of both types of the particles. From this point of view the particles suit for the given measuring and can be used with no worry.

Conclusion

Flow fields on simplified model of MSR using Gas lift was measured by PIV and also predicted by two-phase flow theory. Methodology of measurement and calculation was estaliched.

Particle image velocimetry device and two-phase flow demonstrator (TFD) was used for experimental investigation.

Presently two-phase flow demonstrator is on the reconstruction. Measuring and controlling of heat exchanger and gas input device will be more accurate for future.

Other scheduled updates:

- Measuring and data evaluation improving.
- Inductive flow meter coupled with PIV device.
- Velocity and size of bubbles as a gas-lift parameters function.
- Size of bubbles as a distance from gas input function.
- Different spectrums of bubbles measuring.

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