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Hot wire anemometry for experimental determination of flow distribution in multilayer microreactors

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Abstract

Thermal anemometry with constant wire temperature for characterization of the flow distribution was applied for multilayered microchannel reactors first. A reactor system made by stereolithography was used as a model. The hot wire 400 μm long was placed in front of the microchannel exits 800 μm wide. Using a micrometer table all single channel volume flows were measured in the model reactor in dependence of the overall flow through the reactor. A strongly pronounced core flow through the microchannel body was observed at flows where laminar flow was calculated in the reactor inlet tube. This was a result from the design, i.e. of ratio of inlet tube cross-section area to the sum of channel cross-section areas. Calculating pressure drop of channel and reactor inlet tube showed that pressure drop was approximately 10 times higher in the tube than in the channels. In this special case inlet turbulence helped to equalize the flow over the channels.

Keywords: Hot wire anemometry; Constant temperature anemometry; Microchannel reactor; Microstructured reactor; Flow distribution; Methanol-steam reforming; Nanoparticle washcoat; Layer thickness

1. Introduction

Metallic microstructured/microchannel heat exchangers or reactors with high heat transfer surfaces and heat transfer coefficients have high potential for safe operation of highly exothermic or endothermic processes [1,6]. Low weight and fast dynamics are main prerequisites, both of which are excellently met by microsystems (see also [7]).

Metallic surfaces and small dimensions turn out to be critical issues [3–5], also when trying to apply catalyst coatings to the microchannel walls. A critical issue is a well-defined residence time. Every microchannel may be taken as a small single reactor. Obviously, different diameters resulting, e.g. from non-uniformity of catalyst layers would lead to different residence times.

For fabrication tolerances and passivation coatings a simple approach can be used to show the importance for flow distributions. From calculations the pressure drop difference and therefore the mass flow difference between an 80 and a 90 μm rectangular channel is approximately 27% (assuming constant gas velocity).

For heat exchange properties the following performance loss can be concluded: the difference in surface area between such channels of same length is 11%. Assuming laminar flow (Nusselt number constant) the heat transfer coefficient will be reduced by 11% with such increase in diameter. To compensate the higher mass flow through a 90 μm channel, the heat transfer coefficient should theoretically increase by 14%. Therefore the overall heat flux will be (in sum) reduced by already 25% with a 90 μm channel diameter.

For heterogeneously catalysed reactions things are a little bit more difficult, as performance loss is dependent on kinetics of the reactions occurring on the catalyst. However, there is an analogy as the inner diameters of 80 and 90 μm could result from a 10 or 5 μm thick coating on the channel walls in a 100 μm channel. Assuming half the catalyst mass and the 27% flow increase for the 5 μm thick coating the overall catalyst load (flow per catalyst mass) increases by 154% compared to a 10 μm thick coating.

Effects by manufacturing tolerances and channel blockage have been considered in literature by means of simulation in more detail [9,10]. However, this is only of importance if the tolerances and channel differences are well known. For e.g., for one of the studies [10] the deactivation kinetics of the reaction have to be dependent on the residence time and thus it is an inverse method. For catalyst screening on microchannel plates

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Nomenclature

a	constant in King's law (V^2)
b	constant in King's law (V^4)
ΔP	pressure drop (Pa)
Re	Reynolds number (−)
TD	turbulence degree (−)
$U(t)$	time dependent voltage (V)
$\bar{U}$	mean voltage over time (V)
U'	deviation of voltage over time (V)
v	velocity (m/s)
$\dot{v}$	volume flow (m^3/s)

Greek letters

α	diffusor opening angle (°)
σ	standard deviation

a special flow distributor was developed at the TU Eindhoven [11]. However, this concept, i.e. generating a high pressure drop before entering the microchannels is only eligible when there is a spatial distance between the plates. Severe fabrication errors and or channel blockage due to coatings might yield in a higher pressure drop and thus again maldistribution.

In [8], we introduced a general method based on hot wire anemometry to evaluate the uniformity of catalyst coating in microchannel systems first. This method is a more or less contactless scanning method at the outlet of the reactors and can be used to calculate the integral volume flow of each microchannel from measurements without disassembling or cutting reactor systems into pieces.

Another aspect of flow distribution is the inlet geometry to the microchannels. This has been covered in literature recently by simulation [12]. However, an experimental validation could be useful.

Therefore, we refined our method in this study to cover such issues and focussed on influences of inlet geometry and pressure drop differences between inlet and microchannels. Compared to our previous measurements where continuous movement of the microstructure was available only in one direction (along the channel exits of one foil), the experimental setup was modified by a three axis table and a shorter hot wire (400 μm instead of 2.5 mm) to avoid overlapping of the hot wire with different layers of microchannels in a three dimensional system. The method is surely not applicable for in situ investigation whenever heat exchange is involved since this will have influence on the heat flux on the hot wire but the method could lead to design rules and approval of manufacture of microsystems by testing devices with model gas.

2. Experimental

The experimental setup consisted of a three axis table from *Physik Instrumente (PI)* where the microstructured body is located on the table to be able to perform a scan in all directions of space. Also a turning element was used to vary the angle between hot wire and microstructure and to find the center of one channel. Reproducibility of the positioning system was approximately 2 μm. A stereo microscope was used for initial positioning of hot wire and microstructure. A 400 μm long and 2.5 μm thick hot wire from *Dantec Dynamics* (including control and software) was applied to avoid overlapping of the hot wire with different layers of microchannels in a three-dimensional scan (Fig. 1 a and b). Due to the fact that there is a heat flux to the holders of the hot wire, a smaller portion of the hot wire length might be active, the actual value has not been determined yet. The bend in the hot wire which is obvious from Fig. 1b did

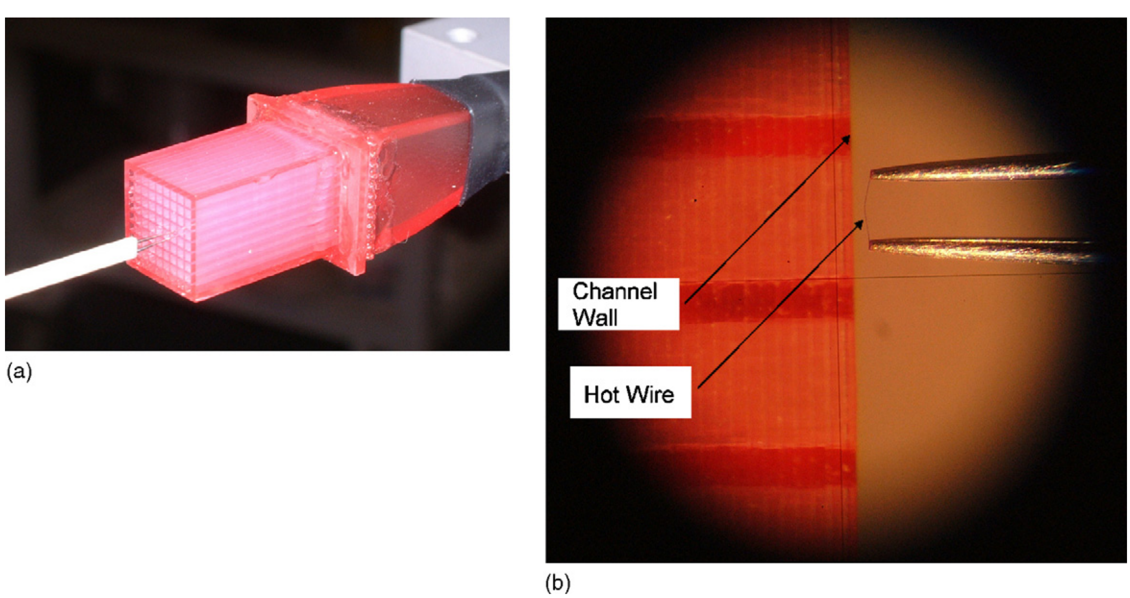

Fig. 1. (a) Scanning the microstructure body in a plane parallel to the microstructure exit (probe sensor can be turned for vertical or horizontal scanning). (b) 400 μm long and 2.5 μm thick hot wire in front of a channel array (channels 800 μm × 800 μm, separated by 250 μm walls) made out of plastics by stereolithography.

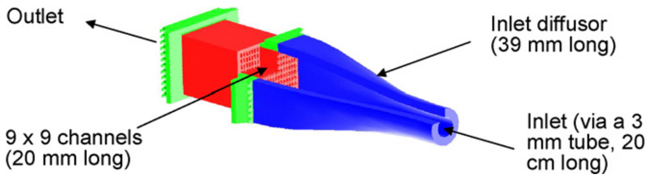

Fig. 2. Microstructured body with inlet diffusor used in this study; the 20 cm long inlet tube is connected to the diffusor.

not affect the reproducibility of the results, which was typically in the range of less than 1% error.

For fabrication of the microstructured body stereolithography was used to generate a simple “honeycomb” with 9 × 9 channels each 800 μm wide and deep, separated by 250 μm walls. This prototype was used in an AiF project for development of a sensor for determination of residence time distribution in microchannels earlier. The channel length was 20 mm. The flow inlet diffusor was designed with a 4° ($2\alpha = 8°$) angle ending in a tube of 3 mm inner diameter (Fig. 2). The tube length in front of the diffusor was 20 cm to ensure fully developed flow at the flow inlet to the diffusor. One of the assumptions, which were made from calculation of the Bodenstein numbers during the AiF project, was a possible maldistribution of flow between the channels. This is why this microstructure was chosen for demonstration of applicability of the method for multilayered microstructures.

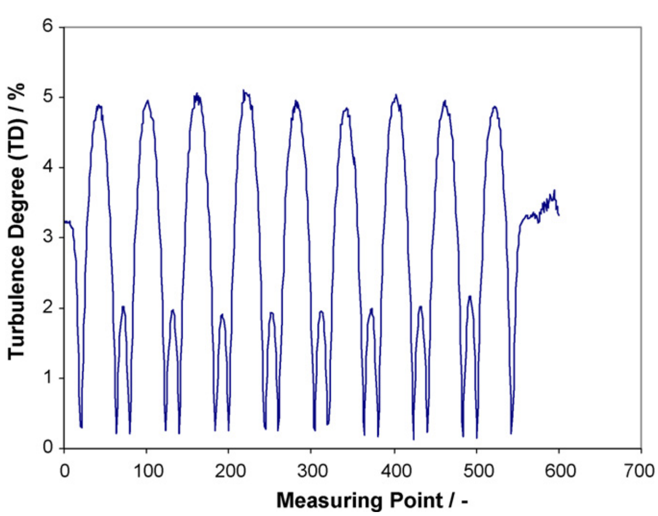

Fig. 3. Turbulence degree at 12 l/min STP along first row of microchannel exits.

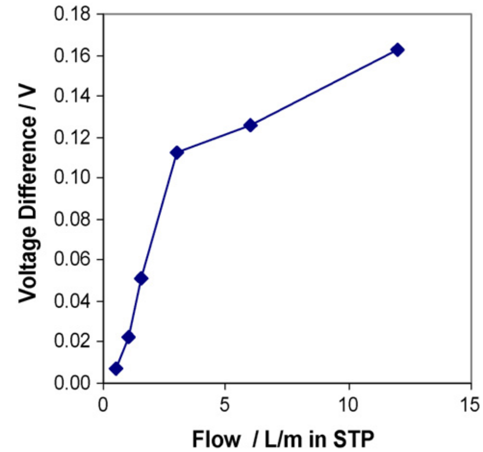

Fig. 4. Mean voltage difference (blank signal subtracted) vs. overall flow through the microstructure.

Measurements were performed with an air flow of 0.25–12 l/min STP by continuously moving the hot wire along the center of each channel row (wire position is rectangular to the movement direction). All measurements were performed at a distance of 385 μm of hot wire to channel outlet to avoid considerable heat flux from hot wire with 280 °C to the microstructure by heat conductivity (see also [2]). However, all measurements were corrected by a “blank signal”, i.e. a measurement without fluid flow. For a total flow of 0.25 l/min STP a smaller distance between wire and microstructured body of 105 μm was needed due to low fluid velocity. The distance between wire and fluid outlet was in all cases proven to be small enough to avoid overlapping or equalizing of flow streamlines at the outlet, e.g. by vortexes (see also [8]). Scanning of the body was performed with a wire velocity of 17.5 μm/s which corresponds to 45 measurement points per channel. For every point 2048 single measurements were used to calculate a mean value of voltage U and a turbulence degree TD with a smallest time constant of 0.4 ms (assuming a stepwise linear dependence between voltage signal and velocity or flow—see later).

$$U(t) = \bar{U} + U' \tag{1}$$

$$U' = \sigma(U(t)) \tag{2}$$

$$\mathrm{TD} = \frac{U'}{\bar{U}} \tag{3}$$

Table 1
Calculated Reynolds numbers and calculated and measured pressure drop as well as deviation of channel flows

Total flow [l/min STP]	Re (channel) [−]	Re (tube) [−]	ΔP (calc., channel) [Pa]	ΔP (calc., tube) [Pa]	ΔP (exp.) [Pa]	$\Delta \dot{V}$ (exp) [%]
0.25	4	97	1	8	Too low	Too uncertain
0.5	8	194	3	17	30	18.8
1	17	389	5	33	50	24.7
1.5	25	584	8	50	90	33.9
3	50	1167	17	100	180	29.7
6	99	2335	38	330	400	8.1
12	198	4670	87	1110	1060	8.1

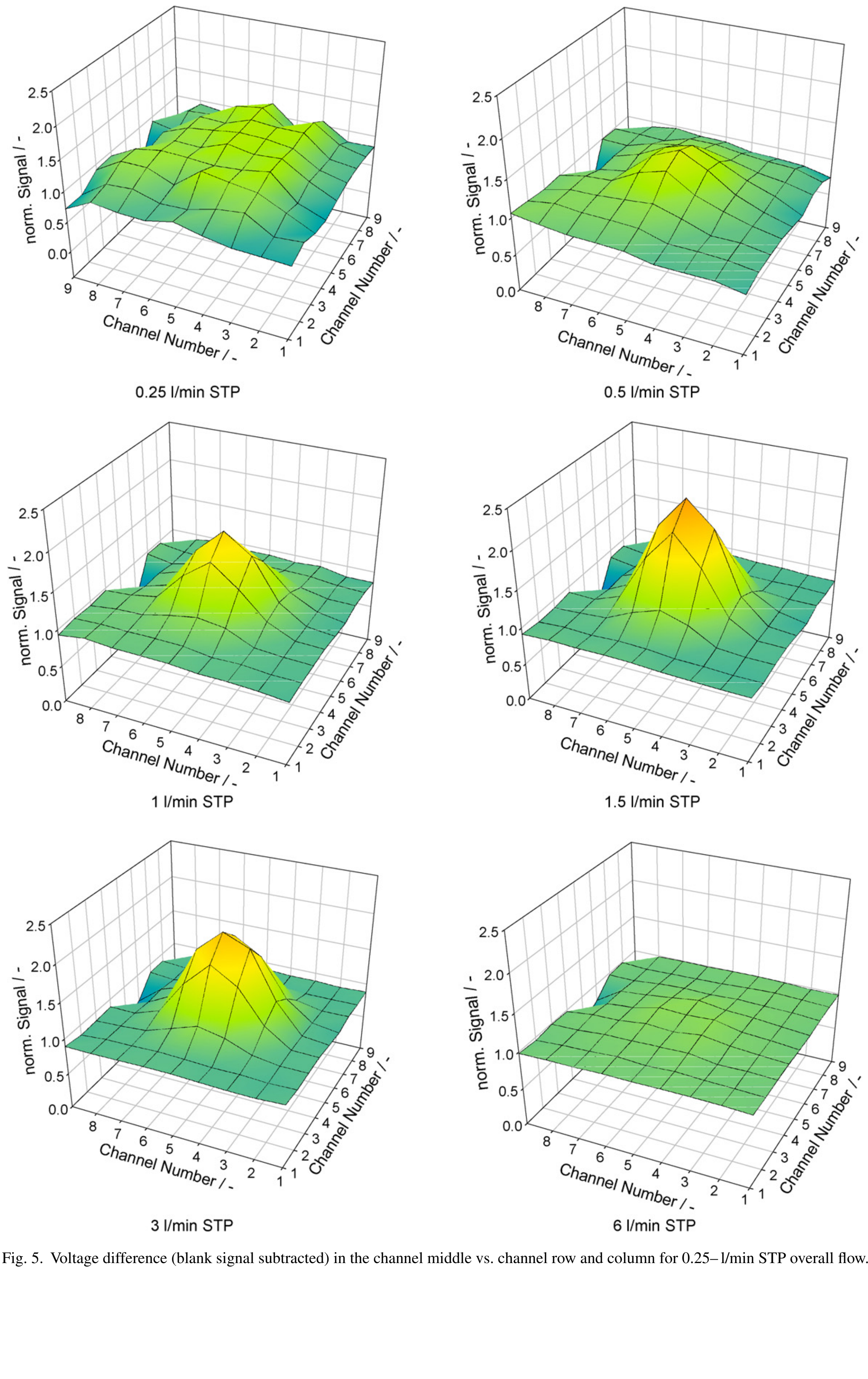

Fig. 5. Voltage difference (blank signal subtracted) in the channel middle vs. channel row and column for 0.25– l/min STP overall flow.

3. Results

In a first set of experiments the turbulence degree at the outlet was checked at the first row of channel exits. The turbulence degree was significant at 6 and 12 l/min STP, i.e. up to 3 and 5%, respectively. At a flow of 3 l/min STP the turbulence degree was in the range of 1% which could indicate nearly laminar flow. This is similar to calculations of Reynolds numbers calculated by using the diameter of the inlet tube, i.e. 1167, 2335 and 4670 for 3, 6 and 12 l/min STP, respectively (see also Table 1 including Reynolds numbers in the channels).

The highest maxima (see Fig. 3) are corresponding with channel middle each. The local maxima in-between indicate that behind the channel there might be a backflow or vortex region.

As far as fluid flow applied was adjusted to interesting conditions which were originally used in this model reactor within the already mentioned AIF project (see “development of a fast sensor for the measurement of the residence time distribution of gas flow through microstructured reactors” by Stief et al. in this special issue), the overall velocities of the gas were much lower than in our previous study [8]. Therefore, we took a close look to the signal to overall flow relation. We generated a mean value of voltage signal from all measurement points in the center of the channels for each total flow applied to the microstructure model (Fig. 4). Obviously the change in flow pattern in the outlet region from laminar to turbulent (at 3 l/min STP) generated a bend so that each region can be treated linear. King’s law [13] predicts a correlation of convective heat transfer coefficient to the fluid with square root of velocity and thus

$$U^2 \approx a + bv^{0.5} \tag{4}$$

However, since there might be a severe temperature gradient along the hot wire due to the heat flux to its holders a different relation could thus be valid. The circumstance of partly linear relation, however, allows a very easy calculation of the flow deviation between the channels at each overall volume flow.

Fig. 5 gives an overview over the overall flow distribution results. A normalised voltage signal (on average) in the center of each channel is shown versus channel row and column for the different overall flows from 0.25 to 6 l/min STP (6 and 12 l/min STP are nearly identical).

Increasing the flow from 0.25 to 1.5 l/min STP increased the maldistribution of flow in the microstructure model. From 3 to 6 l/min STP the maldistribution disappears almost completely. Some irregularities can be seen at the microstructure outer wall, where the flow through 3 channels is significantly lower. This was a result of blocking of the channels by glue which was used for assembling the reactor parts, i.e. inlet diffusor and channel body (see Fig. 2). Highest signals in each diagram are obtained from 0.5 to 3 l/min STP in the center region of the microstructure 3 × 3 channels wide, which is congruent to the inner diameter of the inlet tube into the microstructure body. From these observations we conclude that at very low flows (≤ 0.25 ml/min STP) the diffusor equalizes the flow in a laminar manner, whereas there is core flow in the diffusor coming from fully developed flow of the inlet tube which is continued through the structure. According to calculations (see Table 1) of Reynolds number turbulence can occur at 6 l/min STP in the inlet tube which equalizes then at high total flow the distribution over the foils. However, this effect through turbulence might only occur if pressure drop per channel length is lower than or in the range of the pressure drop per inlet tube length.

Table 1 shows also that the sum of calculated pressure drop in the channel together with the pressure drop in the tube is in the range of the experimentally determined pressure drop over the whole system (including the tube). For e.g. 1.5 l/min STP of air flow the pressure drop in the channels is 8 Pa or per length 400 Pa/m whereas in the pressure drop in the tube is 50 Pa or per length 250 Pa/m. The pressure drop per length seems to be relevant since they are very close to each other. The calculation of $\Delta \dot{V}$ is equal to the standard deviation of U of the measured voltages in the center of the different channels at one total flow where linear signal dependence to the flow is eligible by either having laminar or turbulent conditions. For turbulent conditions in the inlet tube the deviation in channels flows is in the range of only 8% compared to much higher values at laminar conditions in the tube.

4. Conclusion

Concerning the results of anemometry (at the channel outlet) a core flow in the center of the structure was found when laminar conditions were calculated in the fluid inlet tube. At turbulent conditions in the inlet tube the flow was nearly equally distributed over the channels. The pressure drop calculations in the tube and in the microstructured channels showed that the tube pressure drop is much higher than in the microstructure. Therefore, it can be concluded that if the pressure drop in the microstructured channels is not the dominant flow resistance, an equal flow distribution can be achieved only at turbulent inlet conditions. Even an inlet angle of 4° ($2\alpha = 8°$) is not small enough to distribute the flow equally at laminar conditions.

Furthermore, hot wire anemometry was proven to be an excellent technique for quantification of the fluid flow distribution in two-dimensional arrays of microchannels.

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