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JFM van Rens, JT Schoof, FC Ummelen, DC van Vugt, PJ Bruggeman and EM van Veldhuizen

***Abstract* – The plasma of an atmospheric pressure plasma jet strongly interferes with a liquid when it just touches the liquid surface. The gas flow of the jet exerts a force on the liquid surface pushing it downwards, while the plasma exerts a force which is partly counteracting the gas flow induced force. The downward force in the centre of the liquid recipient causes the liquid to circulate with a circulation time of ~2 sec. Due to this circulation the color change of a dye proceeds homogeneously.**

The interaction of plasmas with liquids and biological tissue is currently one of the challenging focus areas in plasma science and technology [1, 2]. It is recently demonstrated that cold atmospheric plasmas (CAPs) have significant potential for wound disinfection and healing [3-4]. In this context of research is performed on Cold Atmospheric Pressure Plasma Jets (APPJs) interacting with liquids.

Plasma liquid interaction can be in the form of heat, radicals, reactive and excited species, ions, (V)UV radiation and electrolysis [1]. All these processes occur at the plasma-liquid interface. Oehmigen et al [5] have shown by visualizing chemical components in the liquid phase that the chemical components from a surface barrier discharge diffuse into the liquid layer. In the case of a plasma jet the situation is significantly more complex due to the flow impinging on the liquid surface which distorts the liquid surface significantly and leads to convective flows in the liquids.

For the measurements presented here we used a 1.1 MHz argon jet developed at INP, Greifswald, called kINPen [3, 4]. The impulse of the argon flow pushes the water level down, the depth of this so-called dimple is determined from photographs of a cubic reactor of 3x3x3 cm which is illuminated by a CW laser sheet. Fig. 1 shows the results for a gas flow from 1 to 2 standard litre per minute (slpm), i.e. a gas flow velocity of ~1 m/s at the nozzle. Higher flows than 2 cannot be used as it leads to severe disturbance of the liquid with leads in some cases to droplets entering the nozzle of the jet. For this measurement the kINPen is positioned such that the edge of the visual plasma emission is at the level of the unperturbed water, see the lower insert in fig. 1. The upper insert of fig. 1 shows the dimple without the discharge on the same scale. Interestingly, the dimple is less deep and more flat when the plasma is on. This means that the discharge is pulling at the water surface. The on-off difference appears to pass through a maximum with increasing flow, however, considering the error bars this effect may not be significant.

The observed effect is not well understood as both ion drag and gas heating would lead to an increase in gas flow [6] and thus in the momentum transfer to the water surface. The presence of a net electrical field (resulting from the plasma sheath) and/or charging of the water surface due to the ion flux are most likely the cause of this effect. Earlier work by Bruggeman et al showed that the presence of low electrical fields can lead to an elevation of a liquid surface [7].

The dimple pushes the water down in the centre of the reactor causing recirculation. This flow pattern is visualized with laser scattering. We used a 250 mW CW YAG-laser to make a sheet that illuminates all the water from the side. With this rather high intensity no additional particles were necessary, as the light scattering occurred on (micro-) bubbles in the water induced by the impinging gas jet. Fig. 2 shows the recirculation zones obtained with a photocamera (shutter time 0.25 sec). From the length of the longest traces on the photo the highest velocity found is 12±3 mm/s. A full rotation takes place in about 2 sec. The water near the bottom also moves but the velocity is roughly a factor 10 lower. Within the accuracy of our measurement there is no difference in the recirculation velocity with plasma on or off.

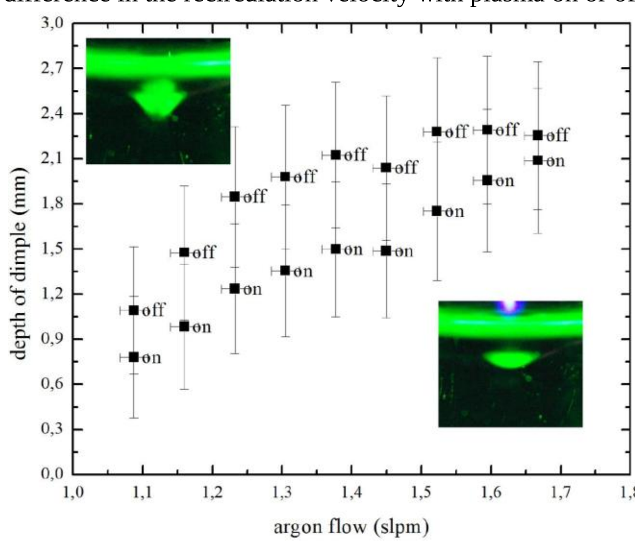

Fig. 1. Measured depth of the dimple at the water surface induced by the gas flow of the jet with plasma on and off. The viewing angle (from below or from the side) makes the dimples look different.

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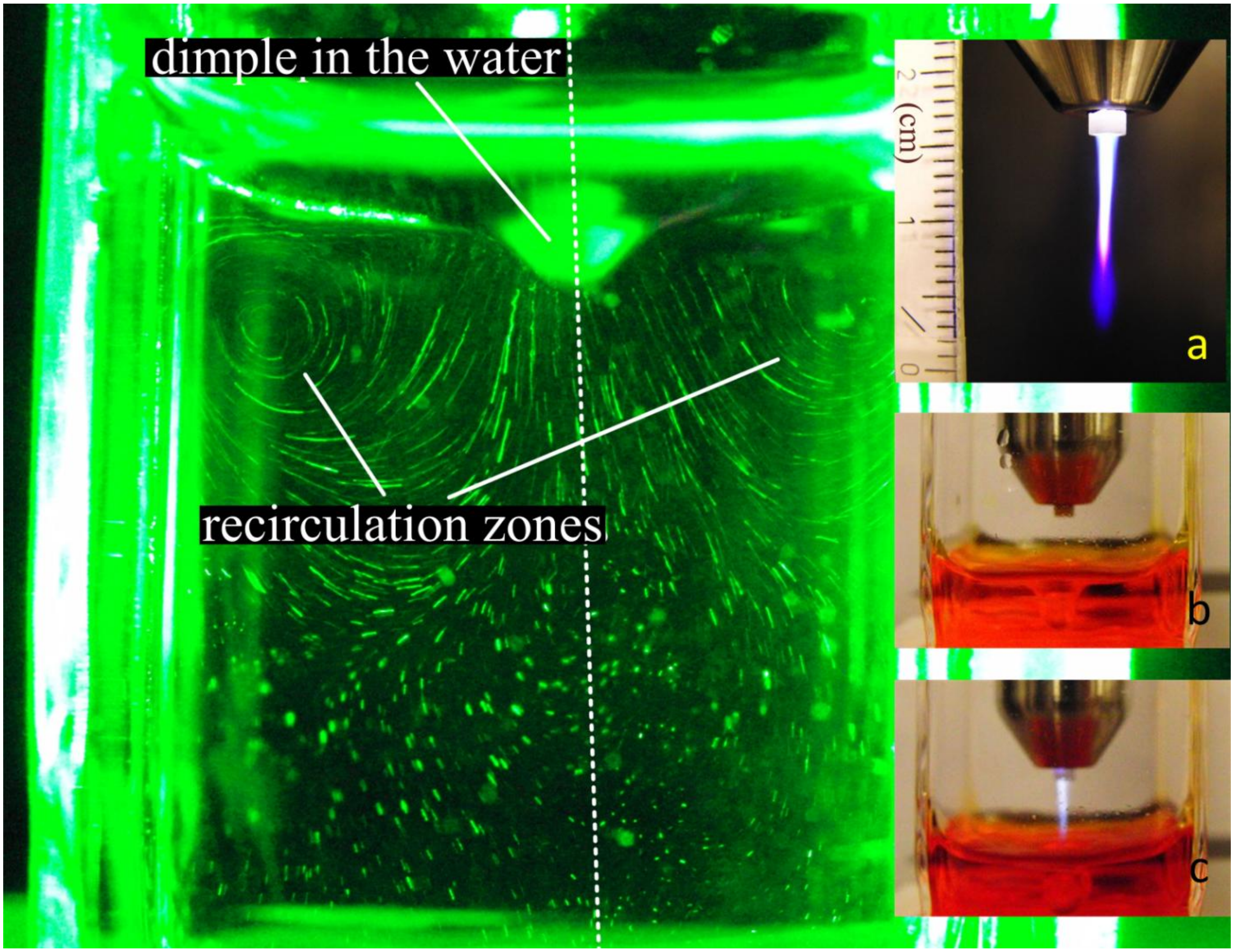

Fig. 2. The flow profile in the liquid recipient induced by the plasma jet and visualized by laser scattering on air bubbles. In this photograph, argon gas was used at a flow rate of 1.9 slpm. The exposure time of the image is 0.25 s. The white light at the sidewalls is due to scattering from the laser sheet. The dimensions of the cuvette are 3 cm x 3 cm x 3 cm. Insert (a) shows the plasma plume next to a ruler with major units of a cm, insert (b) and (c) show a dye sample before and after 10 minutes plasma treatment. The dye color stays homogeneous during the whole treatment due to the induced liquid flow while the color changes from orange to red.

The transport induced by the flow leads to a homogenous plasma induced color change of methyl orange due to acidification (insert b and c of fig. 2). In [5] this color change proceeds through the liquid at diffusion time constants. It is thus very important to consider transport in the liquid during plasma jet treatments.

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