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Positron Emission Particle Tracking (PEPT) for the analysis of water motion in a domestic dishwasher

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HIGHLIGHTS

- We characterised water motion inside a domestic dishwasher via Positron Emission Particle Tracking (PEPT).
- Water distributes detergents and provides the mechanical force required to remove soils.
- Five stages identified: movement inside internal equipment and spray arm, ejection, impact, downfall and recirculation.
- Jet paths were observed to follow a straight line.
- Results have been used to validate Computational Fluid Dynamic (CFD) simulations.

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ABSTRACT

Motion of water inside a household dishwasher has been characterised via Positron Emission Particle Tracking (PEPT). The technique enables the visualisation of the motion of a radioactive tracer in three-dimensional and opaque systems. Results showed a periodic sequence of the water over time, encompassing the following steps: movement inside internal equipment and spray arm, ejection via jets, impact over walls and crockery, downfall (either over walls, crockery or free falling) and recirculation of the bulk water from the bottom of the dishwasher. This sequence was shown to occur within a few seconds and the highest velocities, and therefore, the highest kinetic energies, were found upon ejection. Jet paths were observed to follow a straight line. Increased pump speeds increased velocity ejection profiles, but the effect over the downfall step was negligible. In fully loaded dishwasher (with crockery), the tracer moved slower in these high packing zones, showing low velocity profile areas with higher residence times. Other stagnant areas were found at the edges of the bulk of water remaining at the bottom of the dishwasher. Use of detergent did not seem to affect water motion. Finally, data generated via CFD was compared with equivalent PEPT data, showing good agreement for the spray arm and ejection steps but disagreement in the free falling step. The divergences in the results can be explained by a combination of PEPT data processing and CFD model constraints. Information gathered is helping the development of more sustainable and efficient dishwashing systems.

1. Introduction

Electrical household appliances, such as Automatic Dishwashers (ADW), have eased housework tasks. According to a recent study [1] of consumers in the UK, automatic dishwashing shows important benefits on time saving and water consumption. The typical time needed to load and unload the dishes is around 9–10 min, whilst hand washing the same standardised load [2] could take up to 60 min. The amount of water used by hand washing is around 49 L on average and this amount is reduced to 13 L with a dishwasher. In terms of energy consumption (mostly used for heating water), this study shows a use of 1.7 kWh on average for hand washing and 1.3 kWh for automatic dishwashing. A higher use of this type of household appliances would lead to environmental benefits as a significant proportion of energy and water consumption worldwide occurs in the domestic sector.

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Despite its common use, cleaning processes occurring inside Automatic Dishwashers (ADW) are not simple nor well understood. Scientific information related to dishwashers is scarce and mostly associated to energy consumption and water savings. A heat recovery design from wastewater was studied by De Paepe et al. [3] to heat fresh water and enhance energy efficiency. Weiss et al. [4] analysed the additional potential in energy efficiency that exists for household appliances, including dishwashers. A different approach was followed by Asteasu et al. [5] to demonstrate CAD capabilities on analysing flow pattern problems and geometrical design. Water jets patterns over a plate were used as a proof of concept. However, a detailed study of the characteristics of an ADW is necessary to build the in-depth knowledge and fully understand the wash process.

Dishwashers are complex systems in which a combination of chemistry, temperature, water flow and inner properties of soils are evolving dynamically during a wash cycle. Four areas can be identified: (1)dishwasher design and operation parameters, (2)dishwasher load and type, (3)types of food soils and (4)detergent formulation. The key element that links all areas together is water. It is responsible for the variation in the total cleaning time. Water produces shear stresses over crockery items by direct impact of the water jets, transports the chemistry onto the soils, dissolves certain types of foodstuff and removes low adhesive soils after penetration of chemistry. Therefore, among different parameters, water distribution plays a very important role when analysing the performance of the system.

1.1. Cleaning mechanisms and soil properties

Complex soils mixtures can be found typically in an ADW. Fryer and Asteriadou [6] proposed a classification for cleaning phenomena based on types of soils and mechanisms of removal. Soils were classified based on their physical properties, ranging from *low viscosity fluids* to *cohesive solids*. Cleaning fluids were classified from *water at ambient* to *hot chemicals*.

For cleaning to occur, cohesive forces that bind the soil together and adhesive forces that bind the soil with the substrate must be overcome. If no chemicals are needed and fluid flow is enough, the mechanism can be known as *fluid mechanic removal*. If chemical presence is necessary, a *diffusion–reaction removal* will happen. A combination of different dynamics processes can occur at the same time. These involve mass transfer between the soil-fluid, diffusion of actives species into the soil and reactions of some chemicals that change the inner physical properties. The soil structure is firstly weakened and cleaning eased at the end. Depending on the rate limiting stage, the removal path will occur in a different way.

1.2. Impinging jets

Rotating jet spray arms are used to distribute water in ADW. The coverage produced on the surface by the water jets and the shear stress thus generated are believed to be key factors for the effectiveness of cleaning [7]. The impact of an impinging jet over a flat surface makes the liquid move outward radially in a thin film at high velocity. After some distance 'R' (see Fig. 1), the fluid forms a thicker film as it reaches the film jump. The film jump is defined as the point where a liquid moving fast gets onto a small velocity profile area, producing a sudden decrease in its velocity and thus, an abrupt increase in the liquid height. Then, the liquid drains downwards and forms a falling film of width '*W*'. The term *film jump* is differentiated from the traditional *hydraulic jump* as the latter typically refers to the transition region over horizontal surfaces, where gravity does not affect the fluid flow [8].

Net contributions from gravity, surface effects and the inclination of the impingements coherent jets create a range of down flow behaviours [9,10]. Three common types are known as 'Gravity flow', 'Rivulet flow' and 'Dry Patch' (see Fig. 1). The latter two cases are undesirable for cleaning purposes:

- *Gravity flow:* The liquid drains as a thin film with a width 'W_G'. This width is related to the maximum liquid radius at the impingement proximities. Gravity contributions dominate over surface effects.
- *Rivulet flow:* The liquid film shrinks and forms one or more tails of width 'W_R'. Surface tension effects are in the range of gravity contributions.
- *Dry Patch:* The falling film splits into two. Again surface tension effects are equally important than gravity contributions.

Within an ADW, impinging jets may impact the different surfaces at a wide range of angles. Overall, the same principles are applied. Also, other water distribution patterns are produced: splashing of water due to a jet breaking or falling film generated due to the accumulation of water from top positions. These aspects are hardly quantifiable, and therefore the scope of this work will be focus only on jets movement and characterisation.

Different angles of ejection are obtained by varying the design of the individual nozzles present in a spray arm and by changing the pump pressure. This produces different ejections paths depending on the nozzle considered. Also, the spray arm rotation rate is a consequence of a total torque generated. Generally, the presence of one or more 'driving nozzles' at the bottom of a spray arm creates a net force due to the reaction force (third Newton's law) that is produced on the spray arm once the water is ejected.

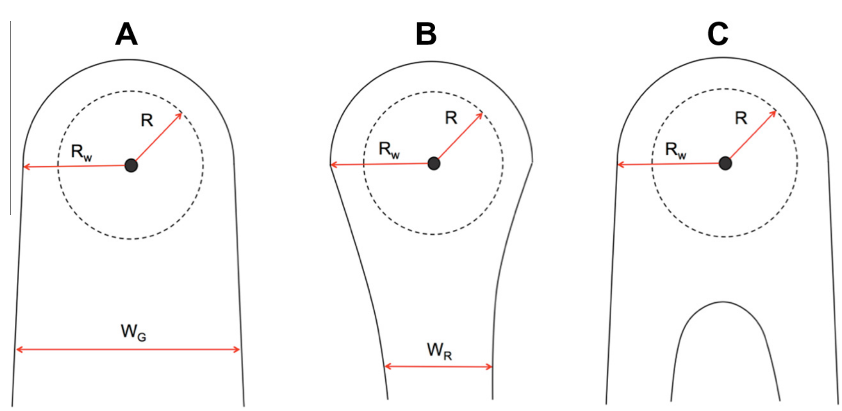

Fig. 1. Drainage flow patters after impingement of a jet over a vertical surface. Black dot represents impingement point. (A) Gravity flow. (B) Rivulet flow. (C) Dry patch. Legend: R = film jump radius; R_W = external circumferential radius; W_G = gravity flow film width; W_R = rivulet flow film width.