Overview on PIV Application to Appliances

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Abstract. The term appliances describes a wide range of products that are used to perform a wide variety of tasks. In the home environment, household appliances like refrigerators, ovens, washing machines, dishwashers, vacuum cleaners, hair driers are sold in million pieces per year; they also have commercial and industrial application. Typical products of the appliance industry have a relatively low industrial cost and the appliance market shows a strong competition, in which appliance technical performance plays a role together with aesthetics and costs. Therefore, efforts in applied research for product technical improvement can be done only if the ratio cost to benefits is advantageous. Many such appliances have complex fluid-dynamic problems; it is important that any experimental technique bears inherent characteristics of simplicity, provides a rapid means to collect experimental data, provides information that engineers can readily exploit for product enhancement, and mostly for computational fluid-dynamic (CFD) code validation. Particle image velocimetry (PIV) satisfies most of the above-mentioned requirements and therefore appears as a good candidate experimental technique to be proposed in the field of appliances. Nevertheless, PIV applications are rare. The PIVNet2 workshop on "PIV application to appliances" that took place in Ancona on June 2003 intended to illustrate the great potential for application of the PIV technique in this sector. This chapter presents an overview of PIV application to appliances according to the outcome from this workshop.

1 Introduction

Fluid dynamics plays a crucial role for a large fraction of household appliances, you have just to think about how important air recirculation is in an oven for the perfect cooking of a meal or the complex multiphase flow that takes place inside a washing machine.

Heat transfer also plays a crucial role in most household applications that is strictly connected with the type of flow involved.

In order to make the product competitive in the current appliances market it is important to improve the efficiency of the system but it is also very important to take care of the aesthetics of the object and sometimes these two things are in contradiction with each other. For this reason, nowadays it is getting more and more important to get detailed knowledge of the phenomena behind each single product, according to its particular shape and working principles.

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Although PIV is widely used by researchers in sectors such as aeronautics, automotive, etc., the appliances field can be considered as a new sector, where at the state-of-the-art applications are almost nonexistent. The PIVNet2 Workshop on “PIV application to appliances” that took place in Ancona on June 2003 intended to illustrate the great possibilities of application of the PIV technique in this sector. This chapter presents an overview of PIV application to the appliance industry according to the outcome from this workshop.

In the following pages the most relevant fluid-dynamic aspects connected with appliances will be indicated together with the problems of applying PIV to this specific sector. In this way, it intends also to be a sort of starting point for researchers and designers that want to use PIV to investigate fluid dynamic of appliances. Moreover, the state-of-the-art of PIV application on this kind of products is shown with some examples of activities already carried out.

2 Fluid Dynamics of Appliances

The large amount of different types of appliances with different types of fluids and flows involved produces a great variety of different fluid-dynamic problems. The temperature is also critical and optimizing heat transfer is important for most applications. We can find a wide range of temperatures from the subzero temperature of the refrigerating applications to the hundreds of degrees Celsius in ovens. The flow patterns are often complicated by walls and structures of the devices and the modulus of velocity can vary from a few mm/s of natural convection flow in a refrigerator to several m/s of the jet of a hair dryer.

In order of give an overview of these problems we present a list of the most common fluid-dynamic characteristics that can be found when investigating flows in appliances.

Type of fluid involved:

- air (almost all types of appliances),
- water (washing machines, dishwashers, boilers),
- gas: (gas ovens, gas cookers),
- other fluids: (refrigerating fluids).

Type of flows:

- free convection (refrigerators, ovens),
- forced convection (ovens, range hoods),
- multiphase flows (washing machines, dishwashers),
- jets (hair driers, dishwashers),
- flames (gas ovens, gas cookers).

Environment:

- open air (air-conditioning systems, range hoods),
- closed environment (refrigerators, ovens).

Temperature:

- subzero (refrigerators),
- below 100 °C (air-conditioning systems, washing machines),
- above 100 °C (ovens).

We can also classify the appliances into several groups depending on their main functions.

Cooking. This group contains appliances used for cooking like electrical ovens, gas ovens and gas cookers. The main problem for this category is to exchange heat in the most efficient way. For this reason air circulation (that can be both free or forced convection) has to be investigated. For gas ovens and gas cookers, a study of flames has to be also taken into account.

Refrigeration. This category contains appliances used to refrigerate and stock food, like home refrigerators, freezers, ice-cream cabinets [1]. In this case we have on the one hand the fluid dynamics of the air circulating inside the device that has to keep the food at the desired temperature, on the other hand the fluid dynamics of the cooling circuit and the refrigerating fluid, with the compressor, the expansion valve, the serpentine and so on

Washing. In this group there are the appliances used for washing, basically washing machines and dishwashers. The fluid dynamics in this case is very complex, a multiphase flow composed of water, soap, air that interact with movable surfaces.

Air conditioning. All the appliances used for air conditioning in houses, offices, shops. In this group we can also include fans and range hoods. In these appliances it is important to investigate the behavior of air both in the environment outside the device to control the efficiency of air recirculation both inside the device to control the efficiency of the air conditioning.

Others. There are a lot of other household appliances with different uses in which fluid dynamics plays a crucial role, like hair driers, vacuum cleaners, but also air recirculation around lamps and hi-fi systems [2].

In Table 1 the fluid dynamics problems in several appliances are summarized.

3 PIV Applied to Appliances

Applying PIV on appliances is not always straightforward. Of course, appliances are not designed for PIV and in many cases they have to be modified to allow the setup of the experiment. On the other hand, on modifying the

Table 1. Fluid dynamics problems in appliances

	Oven	Washing machine	Refrigerator	Air conditioner	Hair drier	Range hood
Fluid	air, gas	water, air, soap	air, refrigerator fluid	air, refrigerator fluid	air	air, steam, smoke
Typical temperature range	60–220 °C	40–90 °C	–30–4 °C	10–20 °C	20–50 °C	room temperature
Type of flow	natural convection, forced convection	multiphase flow jets	natural convection, forced convection	forced convection	jet	natural convection, forced convection
Environment	closed	closed	closed	open/ closed	open/ closed	open/ closed

devices, their normal operating conditions change as well. For this reason it is really crucial when setting up the PIV experiment to try to maintain the product functionality as close as possible to the operating condition in real life.

As seen in the previous paragraph the working fluid in most appliance applications is air, but also water and other fluids are involved, especially in washing machines and in the cooling system of air conditioners and refrigerators. In this chapter only applications with air or gas are considered that are the most suitable for PIV applications.

In order to setup a reliable and safe experiment in this field it is necessary to apply the same rules valid for every PIV experiment [3]. The most relevant aspects are:

3.1 Seeding

In many cases the standard seeding materials used for gas flows are acceptable. Smoke generators and atomizers operating with oil or water can be successfully applied in most applications. In appliances operating at high temperature, like ovens or air driers, oil should be avoided. In this case smoke or atomized water solutions (e.g., water–sugar) are safer and equally effective. In flames, solid tracers like aluminum or titanium oxides can be used.

In some applications, like air conditioners, a very large measurement area is required. Using standard seeding, if tracer particles are small with respect to pixels and are not evenly distributed across the area we can not have clear single-particle images. In this case we obtain gray-level images that can be used to obtain velocity vectors. Anyway, it is advisable to improve the spatial resolution dividing the measurement area in a set of windows.

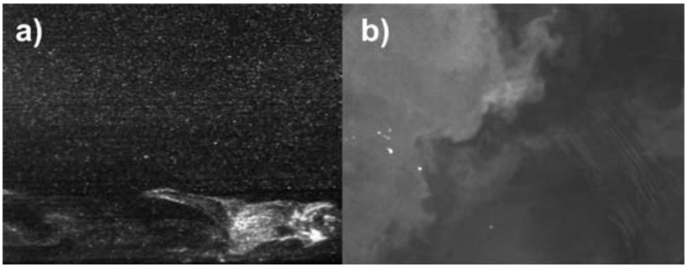

Fig. 1. Difference between a particle image (**a**) and a gray-level image (**b**). In a particle image single particles can be detected, while that is not possible in a gray-level image

The difference between a particle image and a gray-level image is shown in Fig. 1.

3.2 Optical Accesses

When it is necessary to investigate internal fluid dynamic of appliances optical accesses are needed for the laser and the camera. Creating a suitable optical access can be a very critical issue and can compromise the final reliability of the experiment. For instance, in appliances where heat transfer is involved, making transparent windows changes the boundary condition of the problem, introducing a different behavior of the device with respect to its usual functioning.

3.3 Wall Reflections

The most interesting flows in appliances are very often located close to surfaces, like inlets, outlets, grids, fans. Reflections from surfaces introduce a relevant source of optical noise. Mat paint on the surfaces is required in this case to reduce reflections. Fluorescent paint has also been successfully applied. In this case, the wavelength of the reflections is shifted with respect to the illumination source and can be filtered out. Using a Nd:YAG laser ($\lambda = 532\,\text{nm}$) Rhodamine B can be used as fluorescent paint together with a highpass filter.

3.4 Working Conditions

In order to have a reliable experiment it is important to try to reproduce the operating conditions of the appliance in real life. For instance, evaluating the performance of a range hood, the environment around it, like furniture, cookers, boiling pots, should be taken into account as well. In this case, building up an environment simulating a small kitchen can be useful.

3.5 Limitations of PIV on Appliances

The application of PIV on appliances offers many advantages, nevertheless, some limitations have to be accounted for. For instance, the use of high-power laser beams may introduce the need for specific safety regulation. But the main concern is that PIV is a complex technique, which requires qualified staff to be successfully implemented; therefore companies interested in using it should provide training programs for the personnel. PIV is a complex technique because it measures in 2 or 3-dimensional space the multiple components of the velocity (2 or 3). The simplest and common 2D-2C PIV might not be suitable for apparently simple applications, which are actually complex owing to turbulence or the three-dimensionality of the flow.

4 Examples

In this section, some real cases of PIV application to appliances are reported with the double intent of illustrating some aspects of what was explained in the previous sections and showing the state-of-the-art in this field. All the following cases have been presented in the PIVNet2 workshop on "PIV application to appliances".

4.1 Ovens [4, 5]

In the design of gas ovens the uniformity of fume flow patterns in the cooking chamber is very important to obtain the optimum cooking conditions. In Fig. 2a is shown the setup built at Ikerlan to investigate the flow inside a gas oven. To simulate the oven a prototype has been manufactured. This prototype is supplied with orthogonal optical accesses for the laser and camera as shown in Fig. 2b.

The PIV measurements have been acquired by means of a 1248×1024 CCD Camera, a Nd:YAG laser ($\lambda = 532\,\mathrm{nm}$, energy: 90 mJ/pulse) and Aerosil (SiO_2, $0.6\,\mu\mathrm{m}$) as tracer. The oven walls were painted with black and fluorescent paint (Rhodamin B) to avoid reflections.

Figure 3 shows the velocity vectors of the fumes in the tray area of the center of the gas oven obtained by PIV (on the left) and by numerical simulation in fluent (on the right). The comparison between the two vector maps exhibits a good agreement between numerical and experimental data.

4.2 Air Conditioning Systems [6, 7]

Air conditioners are typical appliances where we have problems of external and internal fluid dynamics. Internal fluid dynamics concerns all the flows inside the device, i.e., problems connected with fluid dynamics of the heat

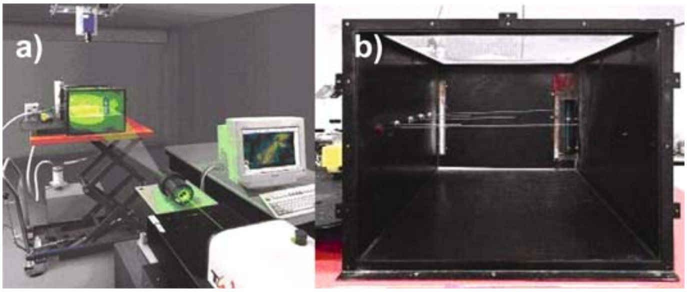

Fig. 2. (**a**) Experimental setup for the PIV measurements in a gas oven at Ikerlan. (**b**) Oven prototype with optical access for PIV measurements

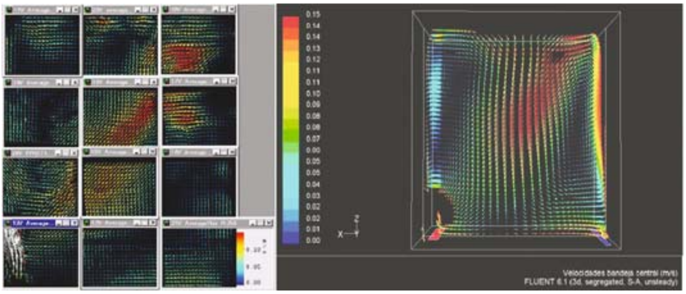

Fig. 3. Comparison between experimental data (*left*) and numerical data (*right*)

exchanger, the fan and the other internal components. External fluid dynamics mostly concerns the mixing of the air coming out from the air conditioner with the air of the external environment.

An example of PIV applied to the internal fluid dynamics of air-conditioning systems is shown in Fig. 4. In this case the region under investigation is the area between the heat exchanger and the fan of a large-size Libert–Hiross air-conditioning system. The PIV images are obtained using a smoke generator for seeding.

Regarding PIV applied to external fluid dynamics of air-conditioning systems the mixing region near the outlet is reported. The PIV measurements have been performed at Sunmoon University Fluid Machinery Lab and a velocity and vorticity map is shown in Fig. 5. In this case, vegetable-oil droplets provided by a six-jet atomizer have been used as tracer particles.

4.3 Range Hoods [8]

Range hoods are very common low-cost household appliances with a rather simple technology. Nevertheless, the design of modern range hoods has to satisfy specific criteria of functionality, ergonomics and aesthetics that can

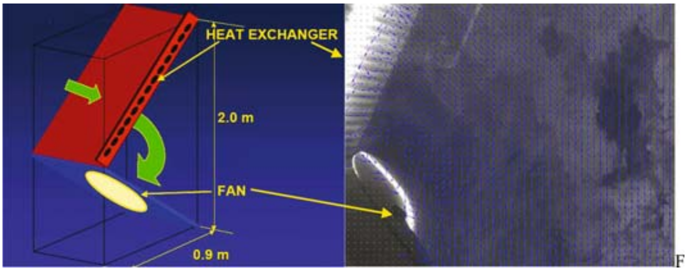

Fig. 4. Velocity vector field and vorticity contour map of the flow in the mixing region downstream of the outlet of an air-conditioning system

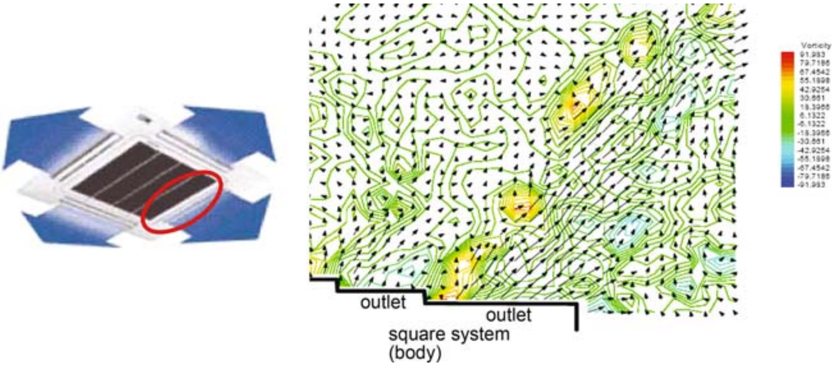

Fig. 5. PIV measurement inside an air-conditioning system. The measurement zone is between the heat exchanger and the fan, as shown in the schematic on the left

not ignore consideration of fluid dynamics performance. A feasibility study of PIV application to the intake flow of kitchen evacuation hoods in operating conditions has been carried out by the Università Politecnica delle Marche. A small environment simulating a small kitchen has been built up (Fig. 6).

An electrical heater and a pot with boiling water has been used to simulate the standard operating conditions of a range hood in a kitchen. The seeding was provided by the steam produced by the boiling pot with the addition of smoke provided by a fog generator.

Figure 7 shows the scalar map of velocity magnitude with streamlines of a small region close to the intake grid. This is part of a study of the interference of the hood's structures with the incoming flow.

4.4 Lamps [9]

The last example is a study carried out by iGuzzini (manufacturer of lighting fitting) on air recirculation around a halogen lamp (Fig. 8). The purpose of this study was to characterize the cooling of the lamp by convective flow in

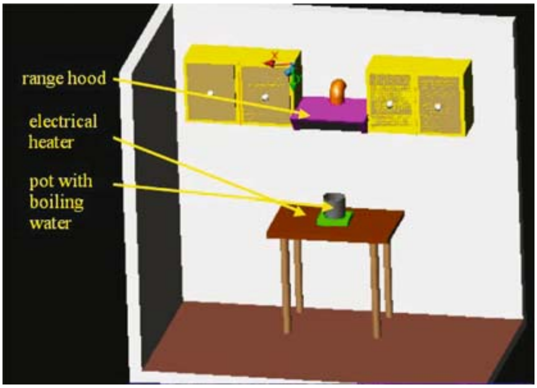

Fig. 6. Environment simulating a small kitchen. The range hood is positioned between wall cupboards and an electrical heater, while a boiling pot simulates a working cooking stove

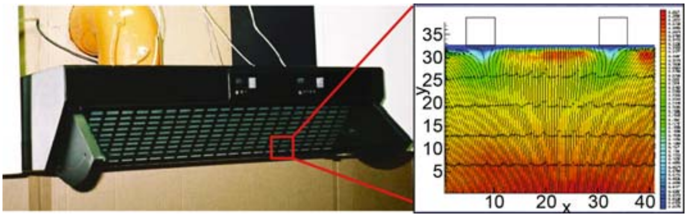

Fig. 7. Scalar map of velocity magnitude with streamlines of a small region close to intake grid

Fig. 8. Halogen lamp produced by iGuzzini object of the PIV investigation

order to design and optimize the temperature distribution in the lamp. In this case, 3DPIV measurements are performed together with CFD simulation.

In Fig. 9 the flow field of two different regions is shown. The top image shows the flow in an axial plane on the top of the lamp that is placed in a vertical position; the bottom image shows the flow in a radial plane with

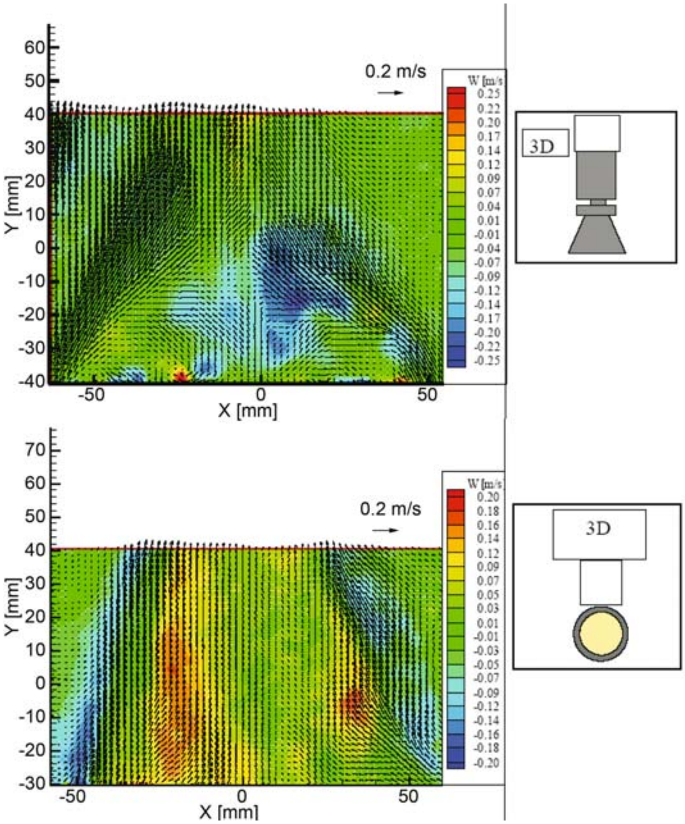

Fig. 9. Velocity vector fields measured by means of 3DPIV in two different regions of the lamp. The contour map shows the out-of-plane component. The velocity field of the two regions shows the strong three-dimensionality of the flow

the lamp placed in a horizontal position. The color map is the out-of-plane component. The flow is a convective flow driven by the temperature gradient between the surface of the lamp that can reach 70 °C and the air. The geometry of the lamp makes the flow strongly three-dimensional, as can be seen in Fig. 9, so that the use of 3DPIV is advisable.

5 Conclusions

Particle image velocimetry has extremely high potential to be used as a tool in the development and design of household appliances and appliances in general. The interest in using PIV in this sector is growing in research institutes and companies, as testified by the contributions presented at the PIVNet2 workshop on “PIV application to appliances”.

The success reached by the event is testified also by the large number of participants.

The event, in fact, was attended by 55 delegates from Universities, enterprises and Research Institutes from all around Europe (Belgium, Denmark, Germany, Italy, Portugal, Spain, Turkey, United Kingdom), from Mexico and from South Korea. Of all the participants only 18 % were partners in the PIVNet2 European thematic network. This testifies to the great interest in this topic also in the world of appliance producers.

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