Shower head design: Increasing performance at lower flow rates

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Abstract

The Market Transformation Programme (MTP) supports the development and implementation of UK Government policy on sustainable products and reduces the environmental impact of products across the product life cycle by collecting information, building evidence and working with industry and other stakeholders. MTP supports the UK Government's strategy on sustainable development and underpins the product policy aspect of the framework for sustainable consumption and production. This study was commissioned by the MTP. A copy of the detailed report (in colour) can be found on the MTP website at http://www.mtprog.com/Publications.aspx (UK Government Shower Performance: Market Transformation Programme – Shower Report).

The UK shower market has a wide range of shower systems with different operating pressures and associated shower head performances. This study will provide a greater understanding of the physics relating to the performance of the spray emanating from a shower head and the potential to reduce flow rate while maintaining good performance. The study is a quantitative approach using computer models validated against experimental data.

Often shower head performance is only judged by visuals of the spray profile. It will be shown that it is possible to maintain a good spray profile at lower flow rates, maximising water coverage on the body, by reducing the size of the holes in the spray head. It will also be shown that water temperatures on the body are only slightly lower using small holes with low flow rates than large holes with high flow rates. The spray profile is also more likely to collapse resulting in collision of droplet streams with large holes. It will be shown that atomiser sprays result in greater temperature loss in transit to the body, well understood in practice, due to the smaller droplet sizes and are therefore not an efficient means of delivery. It will also be shown that surface pressure is extremely difficult to assess.

A wide variety of performance indicators will be discussed including a possible route for manufacturer driven change in combination with educating the users. In addition to the adoption of performance indicators such as time-based products, measures such

as the imposition of flow rate limiters (flow restrictors) through to colour coding of shower heads to match systems correctly when purchasing products and better informing users with flow gauges will be discussed.

Keywords

Shower, performance, flow rate, physics, droplets

Executive Summary

Within the home, water use for showering is increasing as a percentage of overall household usage (currently 13% but expected to rise to 17% by 2020). This is due to householders taking more showers instead of baths and a tendency towards higher flow rate products. The purpose of this study is to determine the potential for reducing water consumption of showering products through numerical analysis.

This study:
- Explores the physics of shower sprays and potential to reduce flow rate while maintaining good performance
- Briefly describes the range of shower systems in the UK market
- Validates computational data against experimental data and British Standards
- Discusses performance indicators and possible options for industry

Initially it was shown, by comparing measured data to computer predictions, that the numerical (CFD) model is an appropriate tool to predict the performance of many types of shower sprays.

The key findings from the CFD model were that it is possible to increase the water coverage over the body at lower flow rates while maintaining the spray profile by adjusting (reducing) the size and optimising the layout of the holes. This can be achieved with a water temperature over the skin that is slightly lower than at higher flow rates. A smaller size of hole will also lead to an increase in the skin pressure.
This work demonstrates that a reduction in flow rate can be achieved without compromising the delivery performance of a shower. Therefore overall savings can be made by manufacturers adopting the analysis techniques suggested in this study.
There is almost a direct correlation between reducing flow rate and reducing energy costs, i.e. half the flow rate leads to half the energy usage and costs.

1. Introduction

The aim of the project is to study different types of shower heads and compare their performances based on a number of criteria such as flow rate and associated comfort. The study is therefore designed to provide a greater understanding in the physics relating to showers and gauge the potential for reducing water usage while maintaining performance. This could possibly lead to the introduction of performance indicators.

Performance indicators can be very wide ranging in their application and across various parameters. Figure 1 shows many types of performance indicators, for example:

- One used to understand complex unrelated and often subjective multiple inputs to provide an overall indication of performance or strengths and weaknesses, e.g. spider diagrams
- A banded approach using a Standard Assessment Procedure (SAP), e.g. an energy rating system
- A direct usage approach based upon one variable, e.g. flow rate for a water rating system

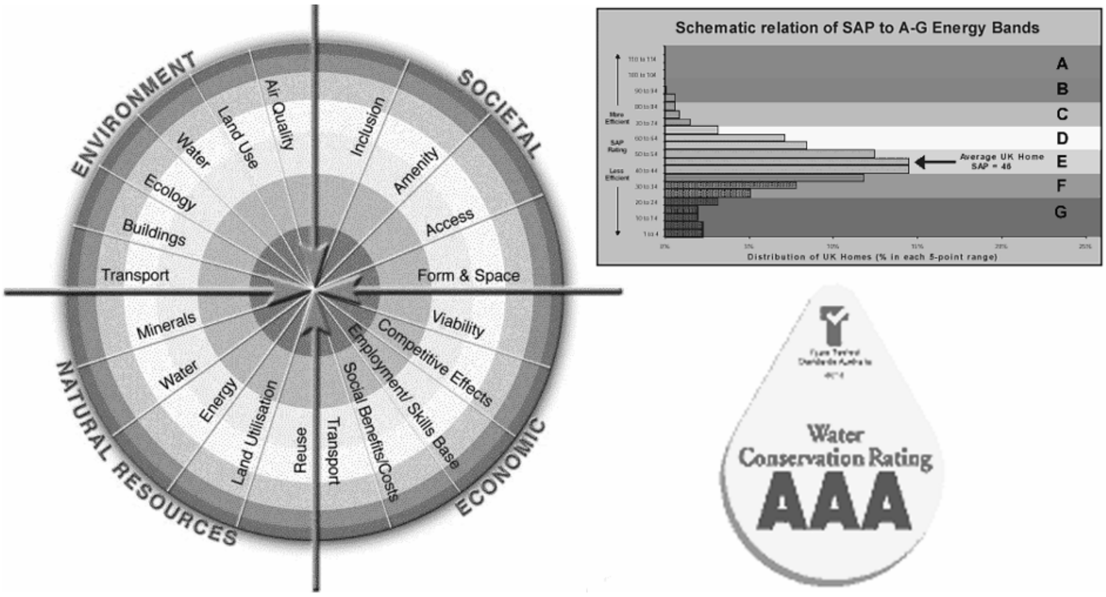

Figure 1: Examples of performance indicators

When we talk about the performance of showers, we can break that down into the four areas illustrated in Table 1 with suggestions for possible subjects requiring further consideration. Of prime concern is water consumption where a certain tested shower product could be related to a rating system or be sold by the length of usage time for an environmentally friendly shower. If energy were to be included in the calculations of performance, then some standardization may be needed in the reporting of usage across different UK shower systems throughout the year which could also possibly include the energy loss within the water from the shower head onto the skin. Objective comfort is the main focus for this study where the quantitative effectiveness of the delivery of water and heat to cover the skin of a mannequin has been assessed. The subjective comfort is more of a qualitative assessment which is the main focus of the work being carried out at Liverpool John Moores University.

Water consumption:	Energy consumption:
• Possible tie in with BREEAM environmental rating system for homes • Time-based approach?	• Standardized reporting for mean operational performance • Consider effectiveness of delivering heated water onto the skin
Objective comfort:	**Subjective comfort:**
• Assess the performance of the shower head • Assess water coverage and heat transfer over the body	• Use appropriate numbers of independent assessors to generate comfort scale • Could be contrary to low water consumption ideal

Table 1: Shower performance indicators

This study uses a numerical approach called computational fluid dynamics (or CFD) to build a virtual model of a shower cubicle (with or without a mannequin) and then outputs a solution of the shower cubicle environment (Figure 2). The cubicle environment is defined by the air movement, air temperature and moisture levels. The environment that a person feels is also dominated by the water movement over the skin and its associated temperature. The impact of the flow rate and temperature of water emanating from the shower head on the cubicle and person environment is also calculated within the CFD model.

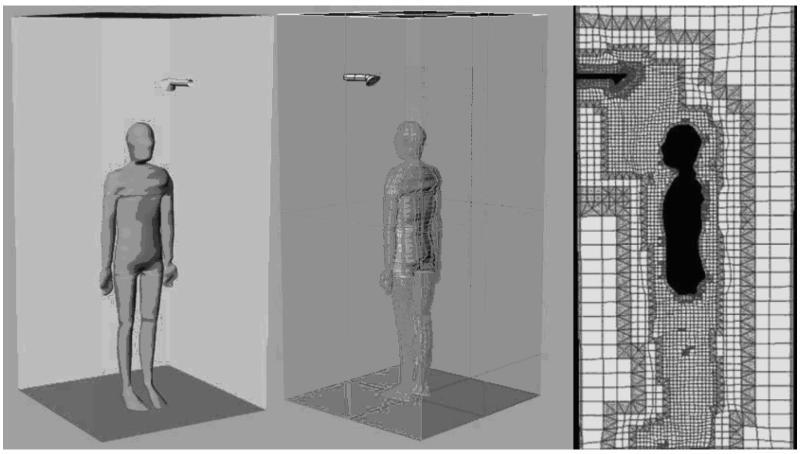

Figure 2: Views of the computational model

2. Experimental data

In order to provide additional confidence in the numerical predictions, experiments have been carried out in parallel to the computational study as part of an ongoing research project under the guidance of Dr David Phipps, Liverpool Centre for Environmental Technology at Liverpool John Moores University. Although the primary purpose of the research work is to examine possibilities for water saving particularly in power showers, a secondary consideration was to provide some validation data to compare against the computational model used in this study.

Flash photography was used to freeze the spray jet/droplets to capture the instantaneous spray form at low and high flow rates (Figure 3). To the naked eye, the majority of sprays look as if they are made up of continuous streams for some distance from the spray head but the photographs and theory based upon Weber number calculations indicate a stream of droplets under the majority of supply conditions with early break up of the jets.

Figure 3: Instantaneous spray form at low (left) and high (right) flow rates

Comparisons were made between measurements at a chosen flow rate and the computational predictions for the same shower head operating at the same flow rate using a British Standard, BS 6340-4:1984, which specifies the requirements for, amongst other things, the functional testing of domestic shower heads.

Spray form was compared using a 150mm diameter annular gauge with 3 measurement zones (centre cylinder, inner annulus, outer annulus). A 60s period was measured at a height where the spray was fully captured to determine the mass and percentage mass per zone to compare against the guidelines and virtual gauge in the computational model. Both the measurements and the predictions were within the desired BS ranges with a maximum difference in any zone of 7% (Table 2).

Zone	% area	BS guidance by zone (%)	Measurements		Predictions		Difference (%)
			Mass (kg)	% by zone	Mass (kg)	% by zone	
Centre cylinder	12.0	0 to 35	1.17	32	1.04	25	7
Inner annulus	32.4	10 to 70	0.86	23	1.04	25	2
Outer annulus	55.6	25 to 85	1.68	45	2.08	50	5
Total	-	-	3.71	-	4.16	-	-

Table 2: Comparison of annulus gauge measurements and predictions

Spray trajectory was also compared with guidance values falling within acceptable limits and, in addition, the water temperature at various distances from the spray head was measured and compared to predictions. Temperatures at each height were measured radially into the shower cone using thermocouples mounted in heat sink so effectively averaging the temperature between the inner and outer spray regions. Similarly, for the predictions, the outer and inner cone temperatures were averaged. The values are given for distances of 0.05, 0.25, 0.45, 0.65, 0.85 and 1.50m from the spray head for similar ambient temperatures and a good correlation is shown (Figure 4). CFD is therefore an appropriate tool for predicting the water droplet temperature variation with height as well as spray form and trajectory.

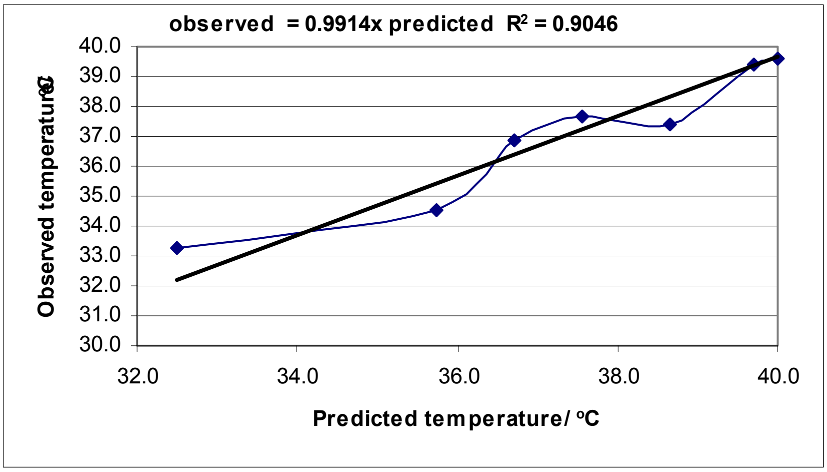

Figure 4: Comparing water droplet temperature variation with height

3. Background to the study

In order to reduce the number of possible variables for the study, a number of different boundary conditions were fixed as follows:

- Surface of the mannequin had a fixed temperature applied.
- Shower head was fixed to an angle of 45˚. The number and definition of the injection points for the spray head represented 16 case scenarios with a fixed water temperature at the injection points of 40°C.
- The case scenarios included variations in flow rate (from 3 to 30l/s), size/number/position of holes in the shower head and, in one case, an atomized spray.
- The shower walls and floor were treated as zero heat transfer surfaces with the top of the shower having a pressure boundary with zero gradient (temperature and moisture).
- The plug hole was again a pressure boundary with zero gradient (temperature and moisture) allowing loss of water.

4. Results

Initial calculations were carried out to determine the appropriate time of analysis when to compare the results from different case scenarios. Figure 5 shows the thickening and running of the water film over the surface of the mannequin and over time from when the shower is witched on. It was decided to take the 5.0 second time period as an appropriate time from which to compare the various case scenarios. In reality, a long shower would result in a steady increase in air and skin temperatures which would require a long-term transient simulation with separate model for skin temperature. This approach is prohibitive for this multi-case study.

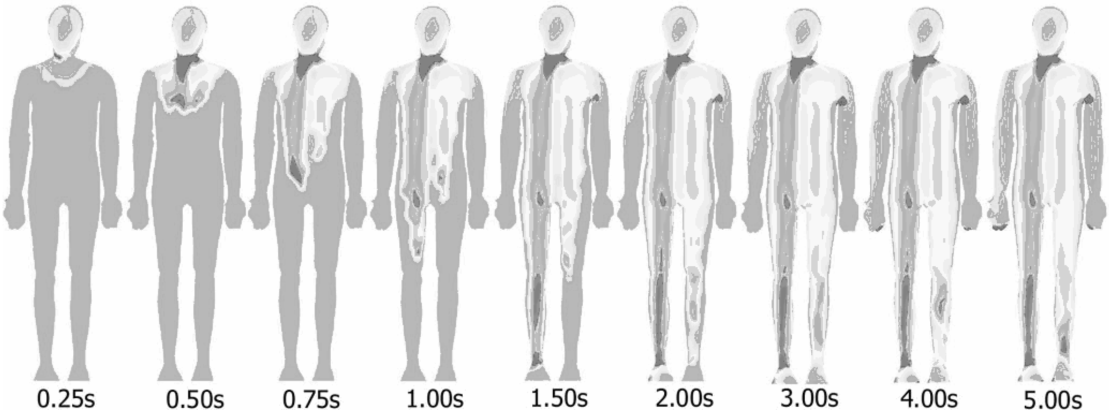

Figure 5: Generation of the water film over time

A number of results were presented for each of the case scenarios to provide a detailed insight to the shower physics. In this paper a comparison will be shown between two shower heads the operation mode of outer sets of holes only. In the first case (on the left in the images) the flow rate is 6.0l/s and it has small holes. In the second case (on the right of the images) the flow rate is 15.0l/s and it has large holes.

The full MTP report contains more detailed information not possible to present here.
Figures 6 and 7 show the predicted air temperature, speed and moisture content distributions on a vertical section through the centre of the mannequin. The change in heat and moisture between the air and water phases is taken into account in the calculations. As the spray passes through the air towards the mannequin, it entrains and heats up the air with the warmest regions (air and water) closest to the spray head with this heating up outweighing the losses due to evaporative cooling. The amount of entrainment and heating up is dependent on the number, size and speed of droplets. The air phase conditions are only slightly different between the low and high flow rate cases.

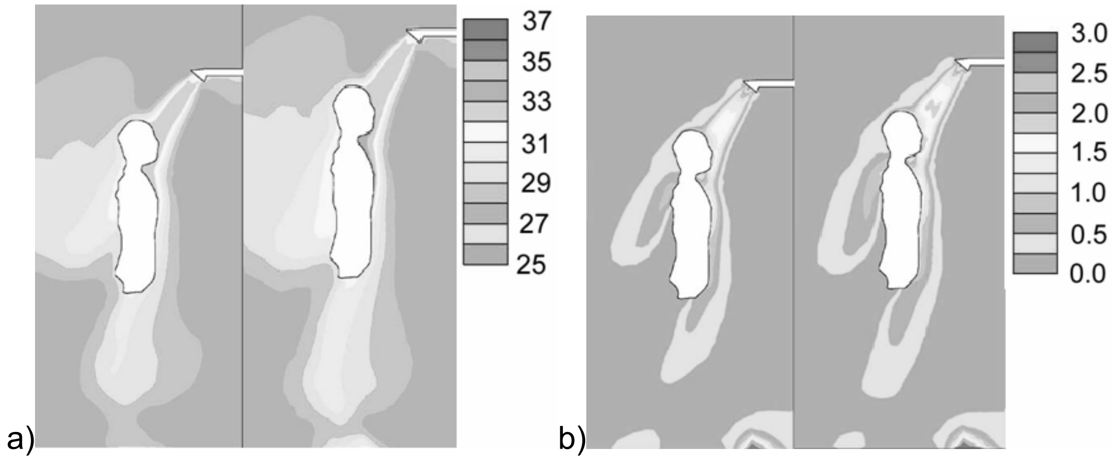

Figure 6: Predicted a) air temperature (in ˚C) and b) air speed (in m/s) distributions

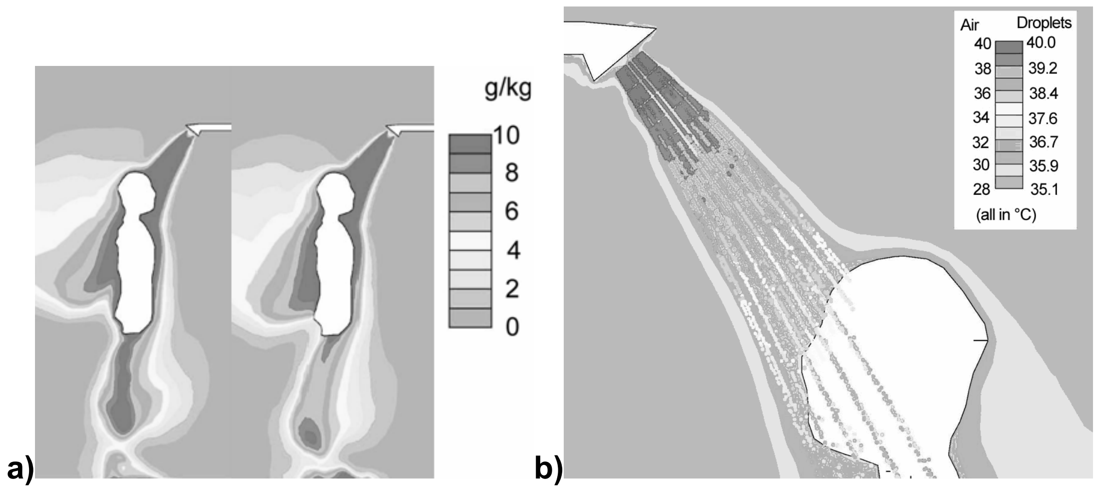

Figure 7: Predicted a) air moisture content distribution and b) combined air & droplet temperatures

Figure 8 shows the predicted heat transfer coefficient and heat flux distributions between the surface of the mannequin air/film next to it. These values vary considerably between spray impact regions, surface run-off areas and non-wetted areas.

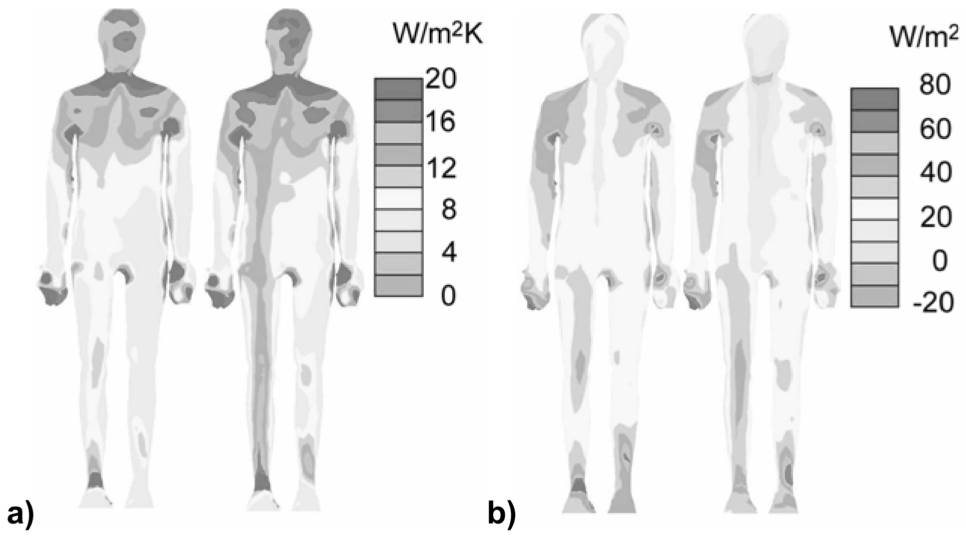

Figure 8: Predicted surface a) heat transfer coefficients and b) heat flux distributions

Figure 9 shows the water film thickness and temperature next to the surface of the mannequin. The mannequin has an undulating surface which causes the water film thickness to vary as it runs down the surface. The location and thickness of the film is largely dependent on the area of impact with the surface and flow rate. In reality this would be ever changing due to the movement of the body within the spray. In the two cases shown here, there is a similar water coverage but with a slightly thinner film thickness in the low flow rate case, i.e. water coverage can be maintained at lower flow rates if the size (and number) of holes are adjusted to maintain the spray profile. The water film temperature only varies by about 1K as well.

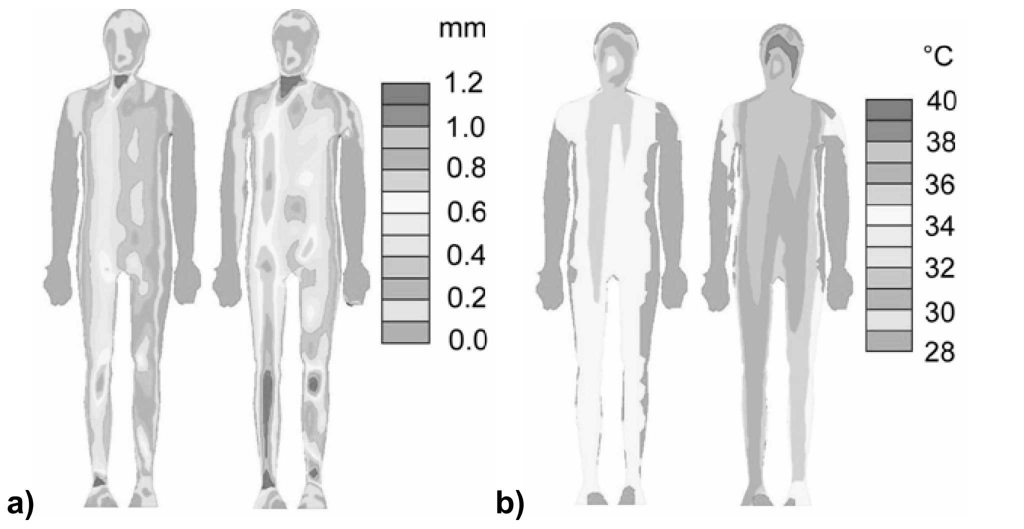

Figure 9: Predicted water film a) thickness and b) temperature

Figure 10 shows the water droplet temperature and pressure (in fact force per unit mass) exerted by the droplets on the surface of the mannequin. The temperature of the droplets reduce as they fall through the air largely because of the exposure of the surface of the droplet to the air, i.e. size of droplet, speed of droplet and the ambient air temperature. The smaller droplets were predicted to have a temperature reduction of about 2.5 to 3.0˚C over the larger droplets. Although it was difficult to assess the true surface pressure due to the complexity of droplet impact at the surface, an indication was provided by calculating surface force per unit mass which showed that the surface pressure is likely to increase with smaller holes, i.e. the size and speed of droplet on impact could therefore be designed to provide a higher surface pressure at lower flow rates.

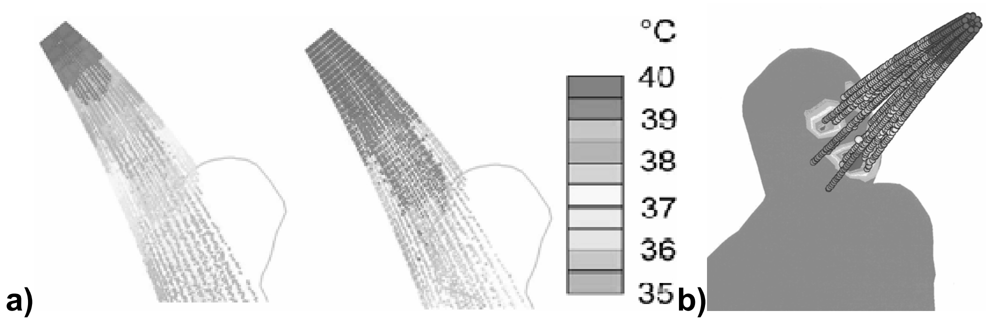

Figure 10: Predicted droplet a) temperature and b) pressure on the surface (or force per unit mass)

For a 15l/min shower at 40°C, energy usage increases by 9% if the supply temperature is increased by 3K but reduces by 60% if the flow rate is reduced to 6l/min (assuming a typical mains temperature of 8°C). At the lower flow rate, energy usage also increases by 9% if the supply temperature is increased by 3K but the overall energy usage is now 40% of that at the higher flow rate, i.e. it is far more economical, in terms of energy usage, to reduce the flow rate and then, if necessary, slightly increase the water temperature to compensate for lower water temperature hitting the skin (smaller droplets). Halving the flow rate leads to halving the energy usage and associated costs.

5. Summary and conclusions

The key physics in the study were as follows:

- Quick break-up of the spray jets into droplet streams
- Trajectories largely dependent on spray head definition, momentum and gravity. Inter-stream collisions will occur with certain combinations.
- Spray interacts with air generating movement and heating it
- Evaporation occurs taking heat out of air and adding moisture to it
- Surface heat flux dependent on air/film coverage and temperatures
- Water droplet temperatures reduce due to exposure with the air and the inner core is warmer than the outer one
- The greatest heat loss is in a spray with smallest size of droplets
- Complex physics within impact region making true surface pressure difficult to assess

The key findings in the study were as follows:

- Water film coverage and spray profile can be maintained at lower flow rates by adjusting size and number of holes
- Water film temperature is slightly lower at lower flow rates
- Water droplet temperature was slightly lower with smaller holes due to smaller droplet sizes
- There is not a significant difference in water coverage and film temperature between having outer, middle or inner sets of rings
- Surface pressure at the skin can be increased at lower flow rates by reducing the size of the holes

The limitations of the work are as follows:

- The geometric and time varying relationship as a person moves within a shower to increase performance in terms of rinsing and water coverage was not included
- Further development would be required to include the effects of hardness of water, amount of hair (surface roughness), body shape and water droplets which are part air, e.g. aerated, champagne and possibly pulsed streams
- Relating the quantitative to the qualitative aspects of shower comfort (and degree of discomfort!)
- Very high flow rate showers have much more droplet parcels to track impacting the required compute times and possibly the hardware requirements for the analysis

Other conclusions are:

- CFD (Langrangian approach) is an appropriate tool for predicting the performance of many types of shower sprays although surface pressures may be problematic.
- A Standard Assessment Procedure (SAP) or British Standard type assessment could be set up based upon the delivery performance of the shower. Consideration of multiple operational modes over a year may be needed.
- Many manufacturer or user drivers may need to be considered for market change. For the manufacturer this could include performance indicators, flow restrictors, strengthening British Standards, introducing a computational assessment scheme and better standardization for the reporting of performance. For the user this could include performance indicators, better purchase information, advertising and increasing consciousness whilst taking the shower.
- There is almost a direct correlation between reducing flow rate and reducing energy costs, i.e. half the flow rate leads to half the energy usage and costs.

6. Recommendations for future work

- Continue work with manufacturers to assist in the analysis of future shower products.
- Further develop the model to allow manufacturers to drive the solution.

7. Acknowledgments

We would like to thank Dr. David Phipps, Liverpool Centre for Environmental Technology at Liverpool John Moores University, for the experimental data taken from a project originated and funded by United Utilities Plc. We have visited a number of shower manufacturers, namely Aqualisa, MIRA and Triton, who provided a good insight to the industry. We would also like to thank Computational Dynamics Ltd for their software support.

8. References

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9. Presentation of Author

Darren Woolf obtained a Ph.D. in fluid mechanics at the University of Leeds using experimental and computational fluid dynamics (CFD) techniques. Since joining Arup in 1995 he has been involved in a large number of building environment and water related projects throughout the world using advanced analysis to assess and optimise the performance of systems.