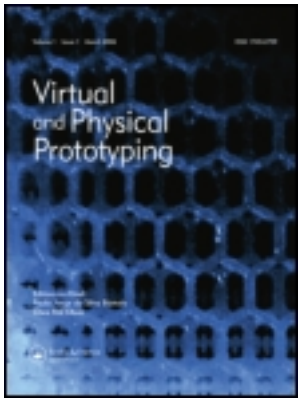
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Rapid prototyping and flow simulation applications in design of agricultural irrigation equipment: Case study for a sample in-line drip emitter

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Rapid prototyping and flow simulation applications in design of agricultural irrigation equipment: Case study for a sample in-line drip emitter

The paper is to study CFD and RP application samples on the design issues associated with agricultural irrigation equipment

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In this study, a 3D CAD solid model of a sample agricultural irrigation emitter was created and the flow behaviour was simulated in its labyrinth channels by using a flow simulation technique. Referenced by the original design, the channel geometry was modified and the emitter was re-fabricated using rapid prototyping/additive manufacturing techniques. The flow behaviour is then re-investigated based on the re-shaped channel geometry of the labyrinth structure. The predetermined optimum pressure in the pipe was validated experimentally for both the original design and modified designs. As a result, the optimum pressure in the pipe and the flow characteristics for original both the design and modified designs of the emitter were validated. This study contributes to further research into the development of agricultural irrigation equipment aided through the utilisation of additive manufacturing and computer aided engineering tools.

Keywords: irrigation drip emitter; design; CAE; rapid prototyping

1. Introduction

Irrigation can be defined as providing water by artificial methods and is necessary if water cannot be met sufficiently through natural rainfall for plant growth during agricultural production (Iscan *et al.* 2007). One of the most useful irrigation methods is drip irrigation and is considered to be the most water-saving technique at present (Zhang 2007, Wei *et al.* 2003a, 2007). A sample drip irrigation system with the necessary components is demonstrated in Figure 1.

Various types of drip emitters have been using for drip irrigation systems. One of the most commonly used drip emitter types is in-line emitters which is one of the key components of drip irrigation systems (Wang *et al.* 2006, Wei *et al.* 2006a,b, Zhao *et al.* 2009). Typically, high or medium density polyethylene material is used for manufacturing the emitters. In the system, the fluid (typically water) is released from the emitters with very little energy, so it drips very slowly into the soil (Palau-Salvador *et al.* 2004). For low discharge rate and high irrigation uniformity, most current commercial drip emitters adopt labyrinth channels with a small flow section (usually less than 1.0 mm^2) (Wei *et al.* 2008). Hence, according to the structure of the drip emitters, the necessity to determine the relationship between flow and optimum pressure in lateral lines is very

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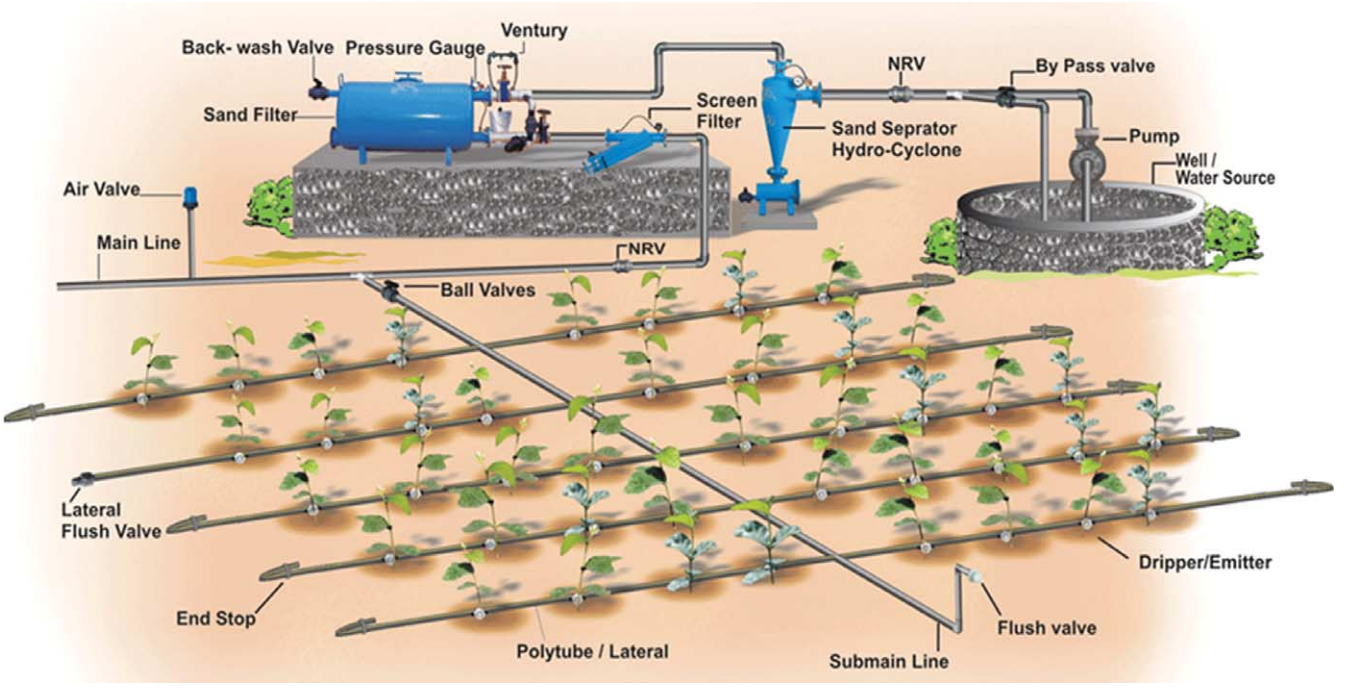


Figure 1. Irrigation system and its components.

important. The following equation (Equation 1) describes the relationship between discharge, $\boldsymbol{q}$ [l/h], and pressure, $\boldsymbol{H}$ [mH_2O] for emitters.

$$q = k \cdot H^x \tag{1}$$

where $\boldsymbol{k}$ is the discharge coefficient and $\boldsymbol{x}$ is the flow exponent. With several data for q–H; $\boldsymbol{k}$ and $\boldsymbol{x}$ can be calculated by using Equations (2) and (3) (Zhao *et al.* 2009)

$$x = \frac{m\sum \log q_i \cdot \sum \log H_i - \sum \log q_i \cdot \sum \log H_i}{m\sum (\log H_i)^2 - (\sum \log H_i)^2} \tag{2}$$

$$\log k = \frac{\sum \log q_i \cdot \sum (\log H_i)^2 - \sum (\log q_i \cdot \log H_i) \cdot \sum \log H_i}{m\sum (\log H_i)^2 - (\sum \log H_i)^2} \tag{3}$$

where $\boldsymbol{i}$ is the iteration number of the data, and $\boldsymbol{m}$ is the total number of the data.

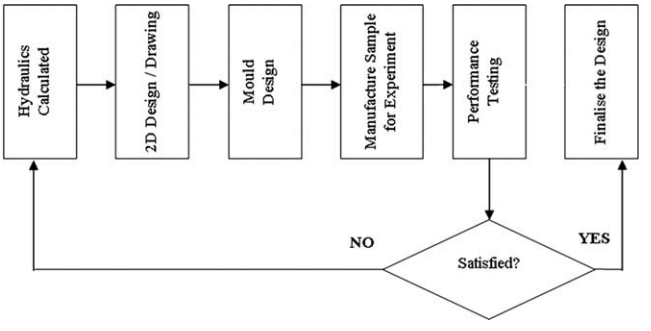


Figure 2. Traditional approach for emitter development.

Equation (1) models the emitter behaviour: this kind of equation is still obtained empirically from experimental studies. However, this knowledge cannot provide additional information about the flow behaviour of the emitter and the optimum pressure in the laterals. Such information of flow behaviour and pressure in the laterals directly affect the designing of the emitters.

In fact, even at present, design development of the emitters is conducted taking into account designer's experiences and iterative experiments. Generally, the procedure is: create an original design by helping with the aid of hydraulic calculations – 2D drawings – mould manufacturing – experiment/test – product finalisation. This traditional

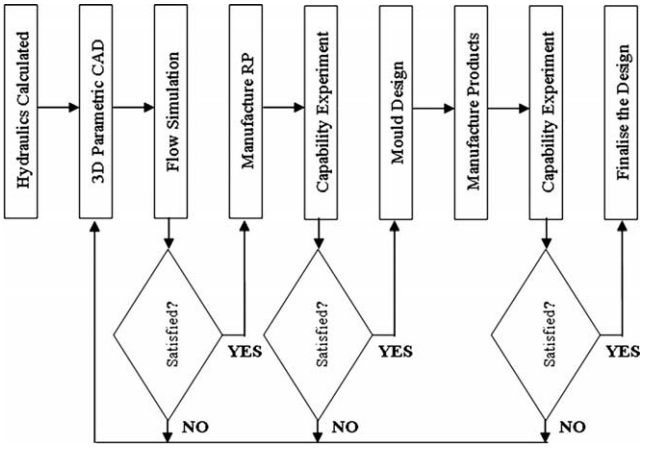


Figure 3. New approach for emitter development.

approach, which is detailed in Figure 2, can take a long period of time to undertake and be a financially expensive exercise (Wei *et al.* 2004). The cycle of design and development is normally 4–5 months, there is no knowledge accumulation, and the accuracy of the product is low (Wei *et al.* 2003b). Additionally, even when using analytic and experimental methods, it is not possible to obtain an exact solution on the effective, desired flow volume at the outlet of the emitters in the field of operation.

Today's developed computers and software, which are used for product development, are now taking their place in the design of agricultural equipment. In the product design area, some of these applications are 3D solid modelling and numerical method simulations. Designers can simulate and determine optimum parameters of their designs on-screen using such computer aided engineering applications. This approach can be very useful to avoid losing time and decrease the costs of the product design and development process. In addition to this, rapid prototyping and manufacturing (RP&M) or Additive Manufacturing (AM) technology has been used to rapidly evaluate product designs since the 1990s. RP&M technology can transform a design concept into a product model automatically, rapidly, and accurately, and the functional parts can be fabricated directly using RP&M technology (Wei *et al.* 2003a). This technology also can be used for the development process of the irrigation drip emitters within a new approach as shown in Figure 3 (Wei *et al.* 2004).

In this study, an in-line type irrigation drip emitter, which is currently manufactured by a company in Turkey, was used. First, according to the desired drip flow volume for a single emitter, the optimum pressure in the lateral pipe was determined using computational fluid dynamics (CFD)

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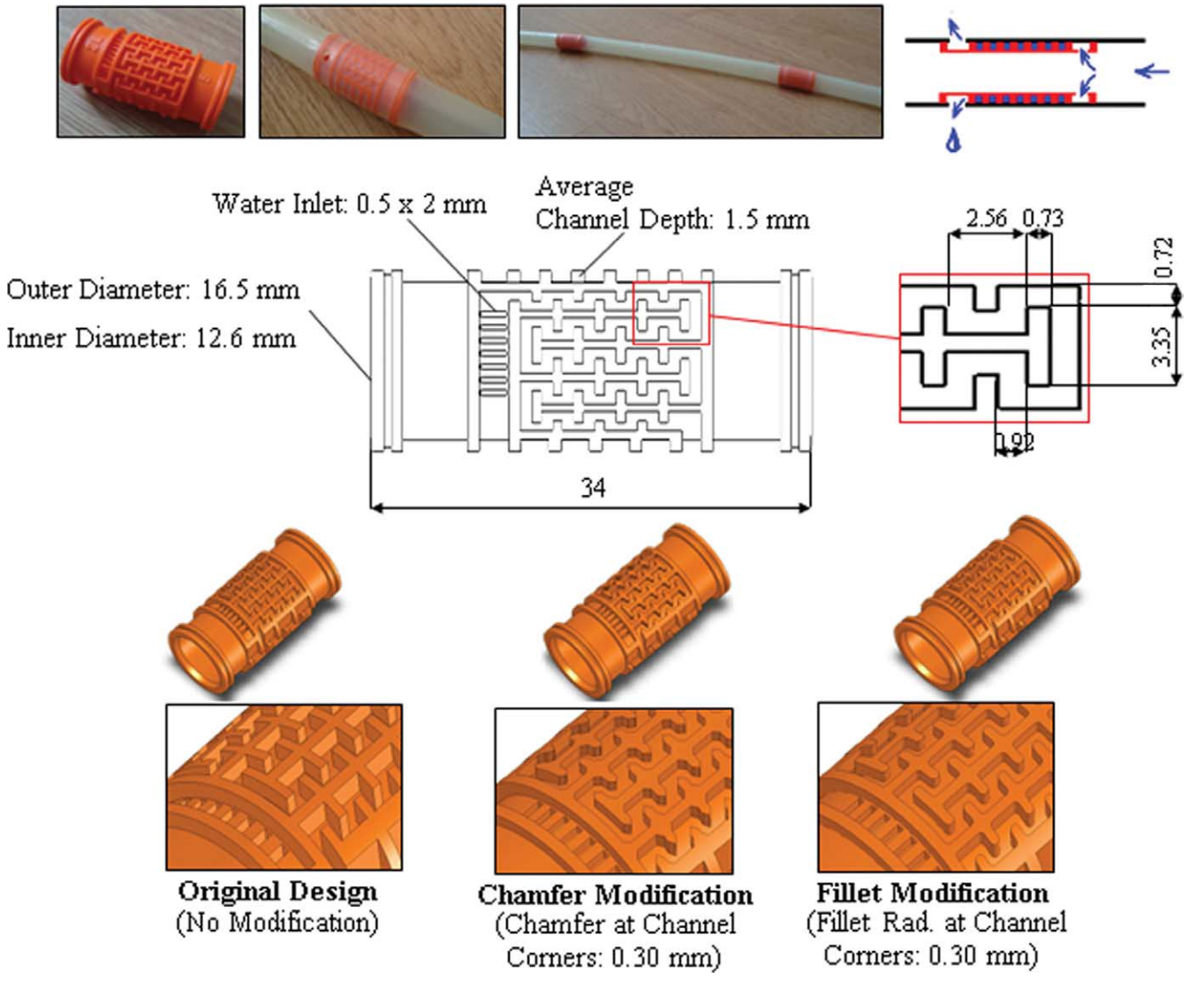


Figure 4. In-line type drip emitter and its 3D solid models.

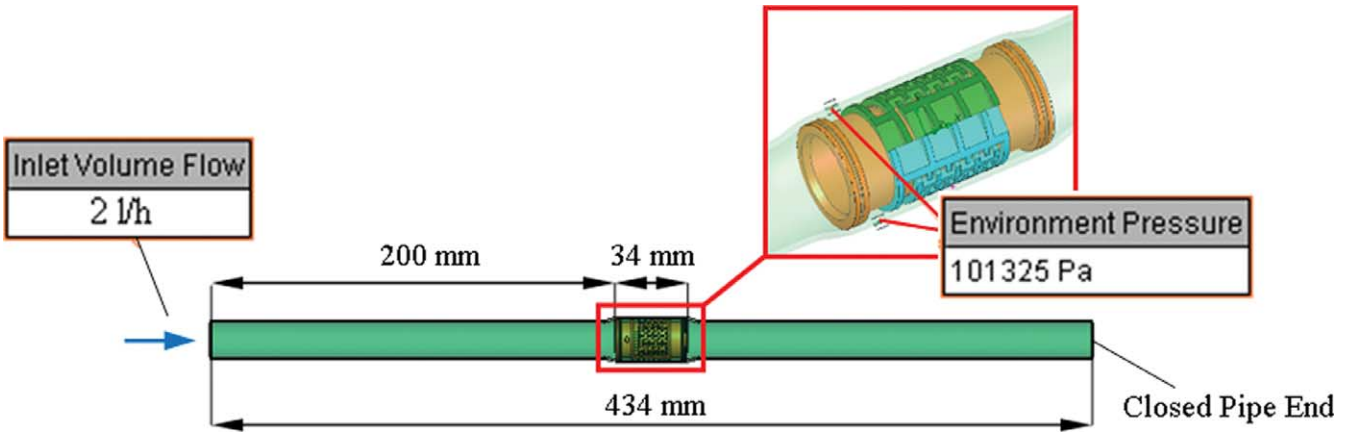


Figure 5. Boundary conditions for CFD analyses.

simulation techniques. Second, to determine how the optimum pressure changes according to the channel structure of the emitter, the channel geometry was modified and CFD analyses were repeated for each geometry. Additionally, two modified emitters were manufactured using RP&M technology and experimental validation was conducted using the RP models.

2. Material and method

2.1 *CAD Modelling*

Computer aided design (CAD) is the use of computer technology for the design of objects, real or virtual. It can be beneficial to use this technology for specific products that have complex and very small structures such as emitters, not only for virtual evaluation before manufacturing but also to obtain time and cost saving on the most effective design. The original emitter utilised in this study, which has a 2-l/h flow volume drip capacity, was modelled in 3D using Solidworks CAD software. Based on this original design, two additional modified emitters, which were re-named as *chamfer modification* and *fillet modification*, respectively, were created. In reference to the manufactured original design, to determine the optimum water pressure in the pipe in the flow simulation, each single emitter was assembled in a pipe which has length of 434 mm. The original emitter and modified emitters are presented in Figure 4.

2.2 *CFD analysis*

The ultimate goal of the utilisation of CFD is to understand the physical events that occur in the flow of fluids around and within designated objects (Lomax *et al.* 1999). CFD methods are concerned with the solution of equations of motion of the fluid as well as with the interaction of the fluid with solid bodies (Blazek 2001). CFD is an increasingly important design tool in engineering and also a substantial research tool in certain physical sciences. The CFD method can help designers select the most rapid and economical approach to conveniently optimising various alternatives, thus significantly reducing the physical work during the experimental stages (Li *et al.* 2009). The CFD method has become an indispensable component of modern emitter design theory (Wang and Wang 2006).

Solidworks Flow Simulation software was utilised to simulate flow behaviour inside the emitter channels and the pipe. A single emitter was assembled into a pipe and boundary conditions were defined in order to provide a 2-l/h volumetric flow rate at the emitter's dripper holes. Values for temperature and pressure during drip irrigation are

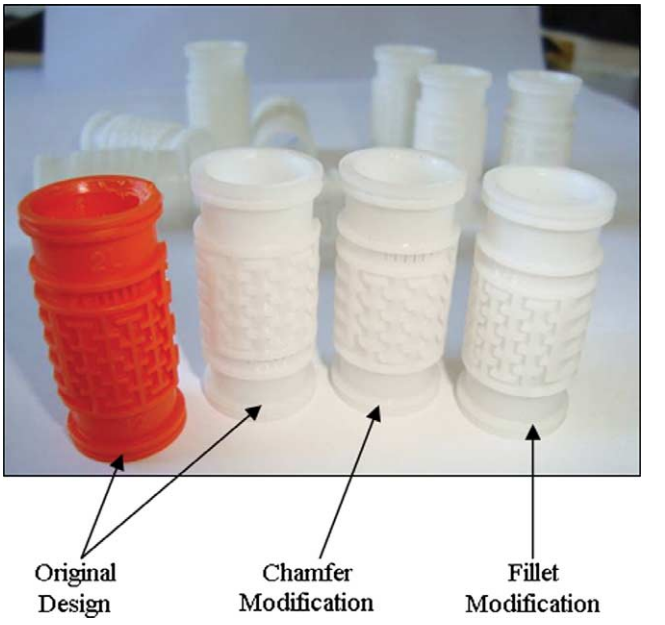


Figure 6. Original design component and SL models of the three designs.

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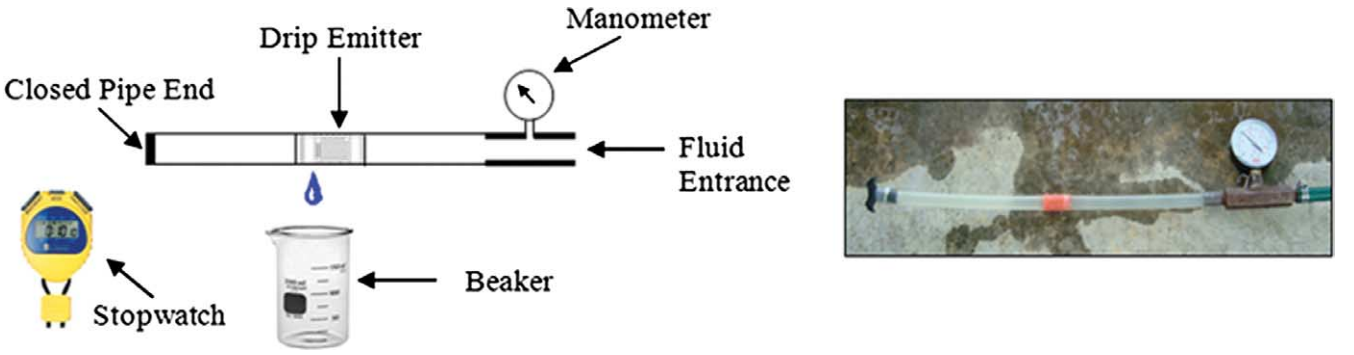


Figure 7. Experimental study.

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insignificant; hence, the fluids in the drip emitters are incompressible. The water head of a drip irrigation system usually keeps at a steady value over the whole work period, which means that the flow in drip emitters has a steady boundary, and need not be treated as a transient problem (We *et al.* 2008). Identical boundary conditions were defined for all three analyses of the emitters. In the analyses, water was assigned as the fluid being emitted and viscous, incompressible flow was assumed at environment temperature of 20°C. Earth gravity was considered for the simulation and surface roughness was assigned as 0.01 mm for the walls of solid models (Palau-Salvador *et al.* 2004). Default mesh function with advanced channel refinement option was applied in the software for the cell structure of the fluid domain. For most flows, it is difficult to have a good estimation of the turbulence so it is recommended that the default turbulence parameters be used in Solidworks Flow Simulation software (SW Product 2010). Turbulence intensity of 2% and turbulent length of 0.185 mm were accepted as default option of the turbulence parameters in the software. The whole calculation domain includes the emitter and the pipe with a rectangular volume of $434 \times 18 \times 16.5$ mm. Inlet volume flow was defined as 2 l/h and environment pressure of 101.325 kPa was defined for emitter's outlet holes which have diameters of 2 mm (Figure 5).

2.3 *RP models*

Rapid prototyping allows for a more simplified approach to the manufacture of individual products that has been previously limited using other, more traditional manufacturing technologies (Smith and Rennie 2009). In order to undertake the experimental investigations, five copies of each of the drip emitter designs (original, chamfer modification and fillet modification) were manufactured using the 3D Systems stereolithography (SL) process. SL was selected as an ideal process as it has the capability to produce the accurate detail required, specifically for some of the very small geometries that are features of the drip emitter labyrinth structure, and the entry and exit holes and grill from the main pipe into the labyrinth structure. The parts were built in layer thicknesses of approximately 0.1 mm.

Although some SL resins are prone to dimensional change from immersion in fluids (particularly water), Somos 9420 Photopolymer resin was selected as it was concluded that this would be suitable for repeated experimentation, and is also chemically resistant should the drip emitters be used with actual agricultural fluids (e.g., pesticides, etc.) in subsequent field experiments.

Figure 6 shows the drip emitters manufactured for this study (the part on the left is the original, the next three are all RP representations of the three designs) and it can be seen that the fine detail within the CAD file has been replicated using this RP technology.

2.4 *Experimental validation*

It is not possible to obtain all real life responses in simulations. Due to the limitations and unpredictability of the material, fluid, dynamic environment conditions, etc., some assumptions have to be made to gain approximate solutions. An experimental study was set up to evaluate how the simulation and real life condition overlaps. The experiments were set up on the original design, chamfer design and fillet design emitters. Simulation scenarios were set up according to the experimental studies for the emitters. In the experiments, the maximum pressure obtained from simulations was provided in the entrance of the pipe and flow volume was measured to determine differences between simulation and experiment. To achieve this, the original design, chamfer design and fillet design emitters in a pipe, manometer, beaker and a stopwatch were utilised and flow volume was measured for pressure of 130 kPa (Figure 7).

3. Results and discussion

According to the simulation results, the effect of the labyrinth structure of the emitters on pressure and velocity is clear. The pressure distributions obtained from the simulations for the three designs of the drip emitters show

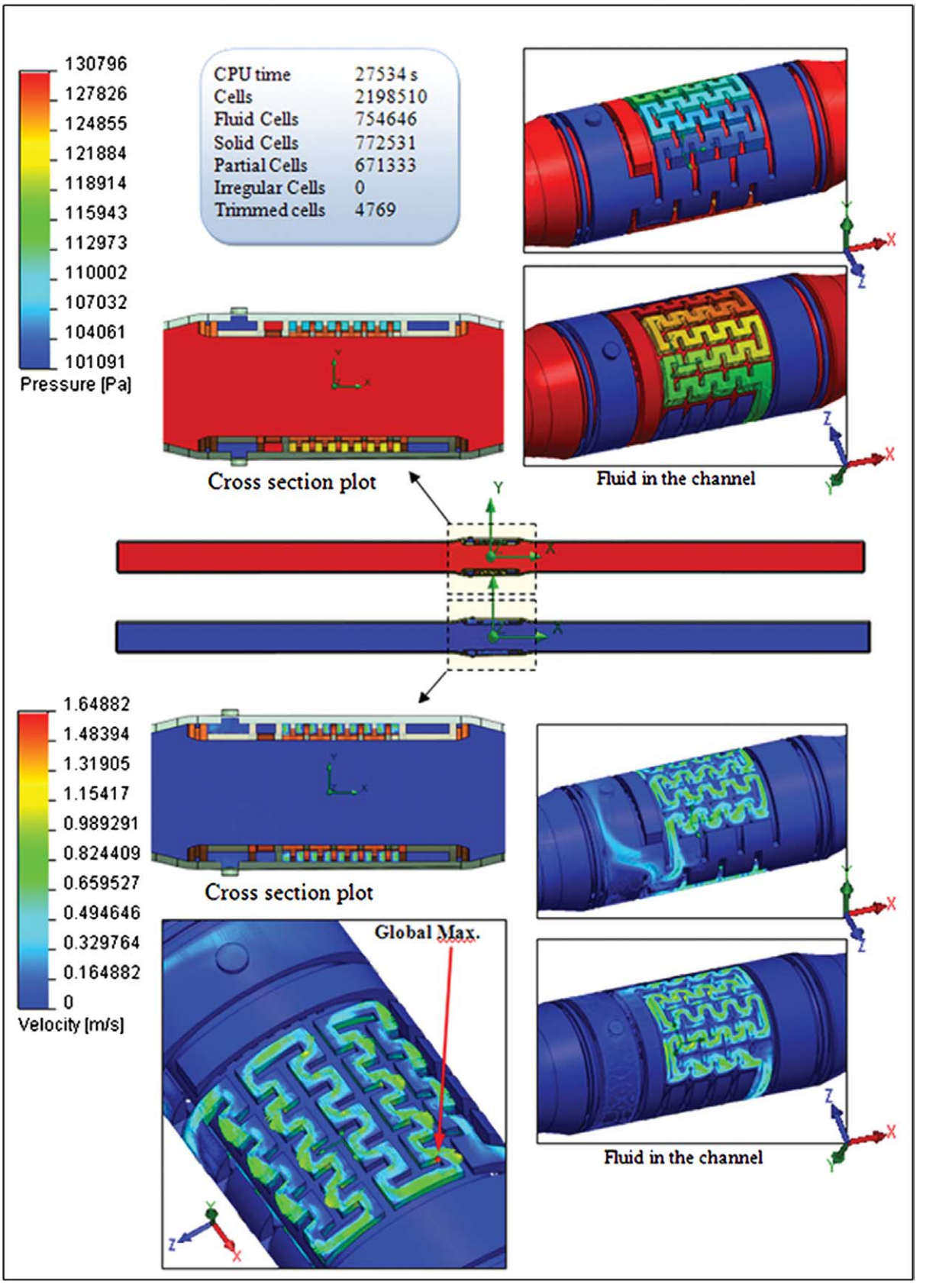


Figure 8. Simulation outputs for the original design.

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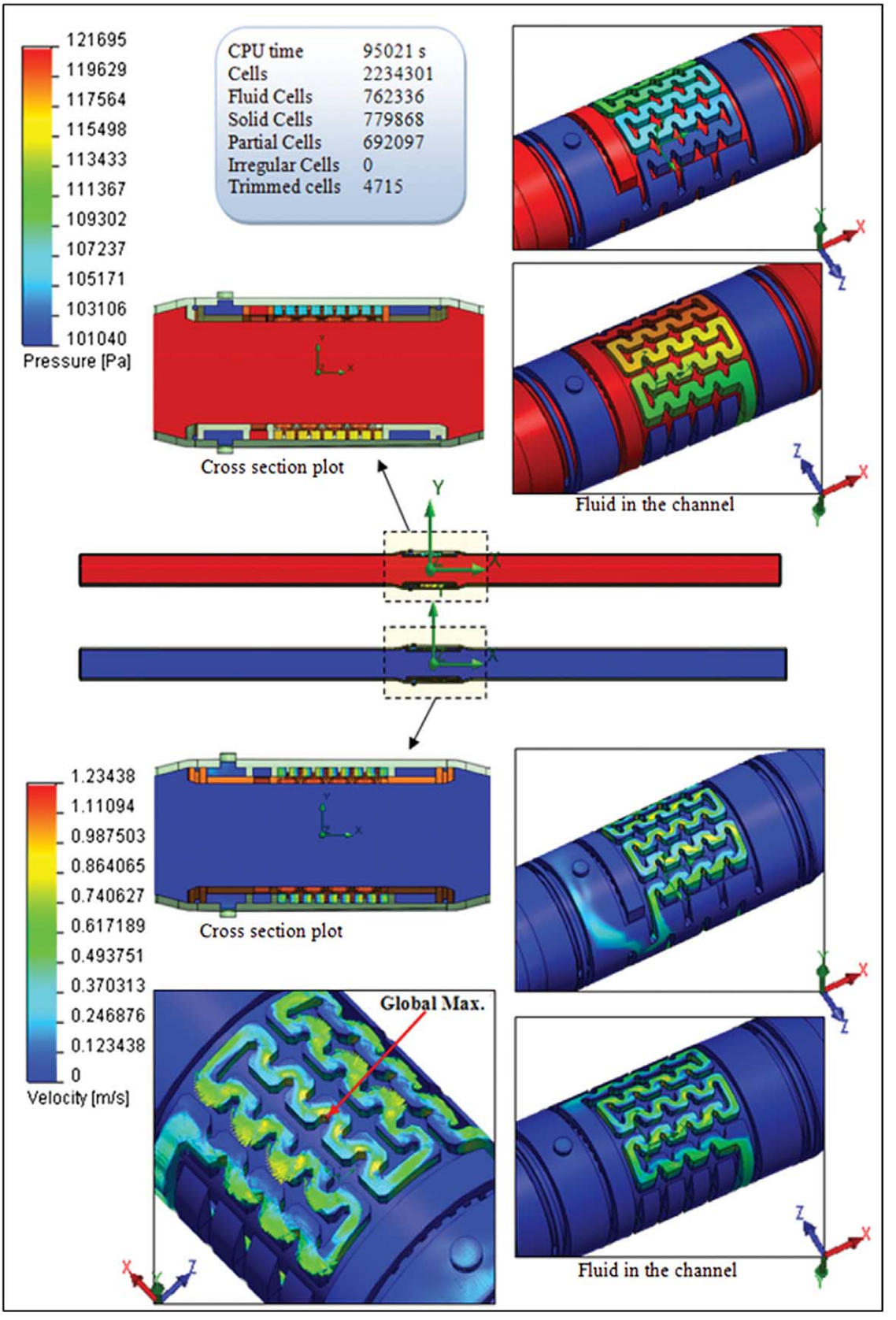


Figure 9. Simulation outputs for the chamfer modification.

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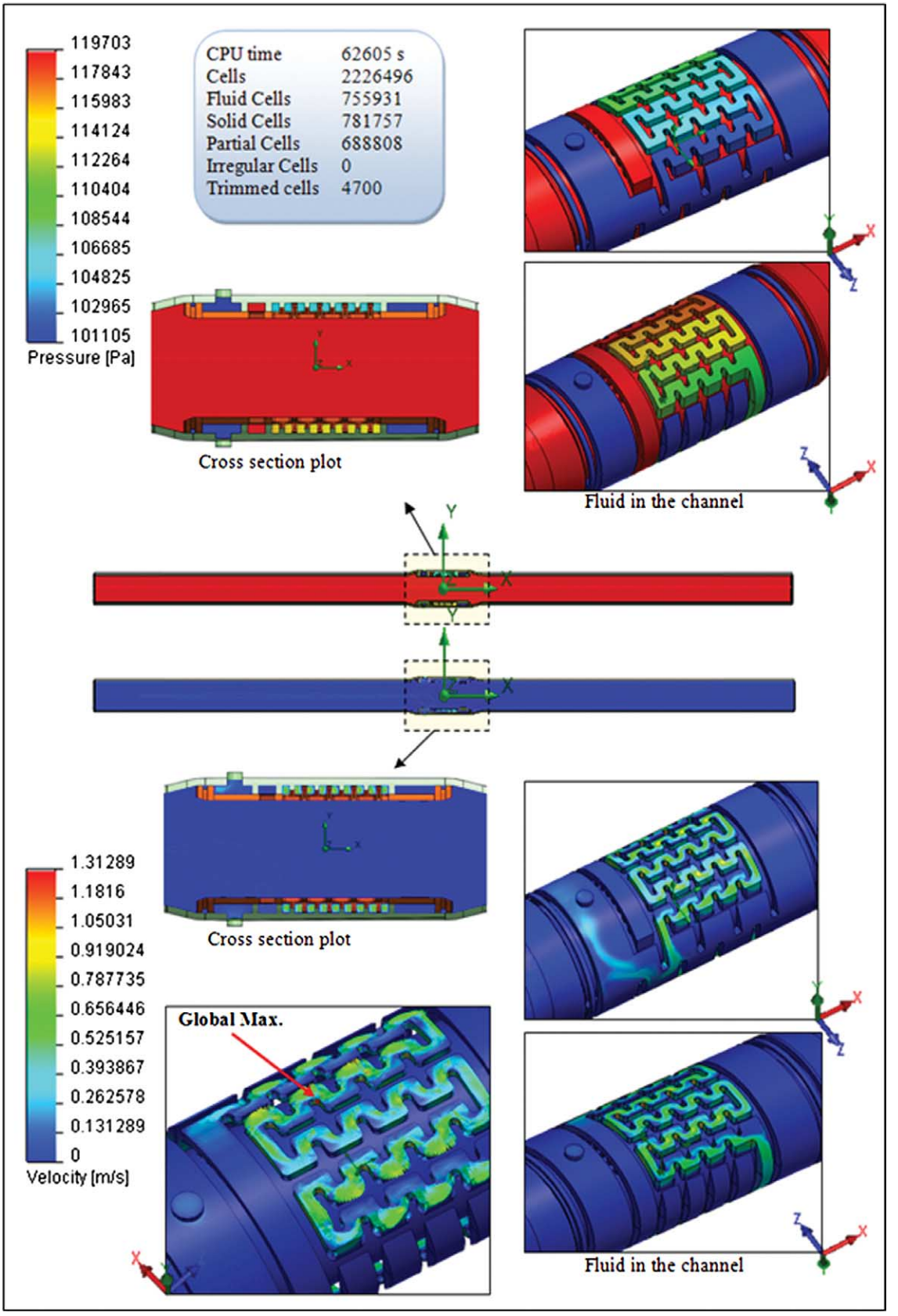


Figure 10. Simulation outputs for the fillet modification.

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Table 1. Simulation and experimental study results

	Original design		Chamfer modification		Fillet modification	
	Global Min.	Global Max.	Global Min.	Global Max.	Global Min.	Global Max.
Velocity [m/s] (simulation)	0	1.648	0	1.234	0	1.312
Pressure [kPa] (simulation)	101.091	130.796	101.040	121.695	101.105	119.703
Volume [l/h] (simulation)	2		2		2	
Pressure difference [kPa] (simulation)	29.705		20.655		18.598	
Pressure [kPa] (experiment)	130		120		120	
Volume [l/h] (experiment)	1.84 ± 0.028		1.76 ± 0.033		1.79 ± 0.029	

that an obvious pressure difference exists in each of the three drip emitter channels (Figures 8–10). The geometry of the corners of the labyrinth channels are the main reasons for the hydraulic energy loss. When the flow turns the corner, the change in the direction of flow results in a large loss of the hydraulic energy. Therefore, in each type of drip emitter channel, the global maximum velocity occurred just before the corner of the channels. The more the pressure varies, the greater the pressure loss will be. The highest difference between global maximum pressure and global minimum pressure was 29.705 kPa, calculated from the original design drip emitter (see Table 1). Therefore, the maximum pressure loss was obtained from the original design drip emitter. Some obvious whirlpools form in the channels of the three designs of the drip emitters. These whirlpools will increase the loss of hydraulic energy (pressure), and the velocity of the flow along the length direction determines the discharge. Comparing the distributions of velocity and pressure along the flow path in the three channels, the original design has the highest velocity and pressure differences along the length of the channels.

Experimental study results for the three designs showed that there is a difference between simulation and the real conditions. The differences on flow volume are approximately 0.16, 0.24 and 0.21 l/h for original design, chamfer modification and fillet modification, respectively. Flow volume experiment results are lower than the simulation by approximately 8, 13 and 10.5% for the original design, chamfer modification and fillet modification, respectively. It can be concluded that this is an acceptable outcome as the accuracy of the simulation results is related with density of the mesh/cell structure of the model, boundary conditions and assumptions made. Referenced by the original design experiment, it is possible to predict how the modified designs' flow volume and resultant pressure in the laterals change for real conditions as well.

4. Conclusion

In this study, CFD and RP application samples on the design issues associated with agricultural irrigation equipment has been presented. A sample in-line type drip emitter which was manufactured by a company in Turkey was used. Referenced by the original design, modified designs were derived and CFD analyses were carried out to observe how the labyrinth channel structure and geometry affects the flow pressure and velocity in the pipe and channels. Differences between simulation and real conditions were investigated by an experimental study. RP models were manufactured to conduct an evaluation and to undertake visual investigations.

According to the study, a number of points can be summarised as follows:

1. Designing, modelling and manufacturing procedures for the in-line type drip emitter is quite difficult with traditional methods because of the small geometries and complex labyrinth structure of the channels. The use of CAE and RP technologies therefore provide very important advantages.
2. In the flow simulations, maximum global pressures in the pipe for emitter discharge of 2 l/h were calculated as 130.796, 121.695 and 119.703 kPa for the original design, the chamfer modification and the fillet modification respectively.
3. In the flow simulations, maximum global velocity in the channels for emitter discharge of 2 l/h were calculated as 1.648, 1.234 and 1.312 m/s for the original design, the chamfer modification and the fillet modification, respectively.
4. Differences of approximately 8% (0.16 ± 0.028 l/h), 13% (1.76 ± 0.033) and 10.5% (1.79 ± 0.029) for the original design, chamfer modification and fillet modification, respectively, were observed on flow volume between simulation and real conditions in the results of the experimental study. Such differences are acceptable within the field of study.
5. According to simulation results, it was seen that chamfer and fillet modifications were in need of a lower pressure than the original design for the desired flow volume.
6. The use of RP technologies, in this case SL, to modify the designs and produce physical variants has proven to be a successful, low-cost method of verifying the design changes with all geometric features being reproduced

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without any significant problems. Additionally, the RP models performed adequately in the physical experiments conducted.

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