A review of the opportunities presented through the application of Computational Fluid Dynamics (CFD) to water management challenges

D.S. Jarman
The University of Exeter, UK (Hydro International based KTP Associate)

M.G. Faram
Hydro International plc, Clevedon, UK

G. Tabor
The University of Exeter, UK

D. Butler
The University of Exeter, UK

ABSTRACT: The current climate of interest in water-environmental issues has lead to increased use of advanced computer-based simulation techniques in the evaluation and improvement of water management systems. This paper reviews the usage history of computational fluid dynamics (CFD) techniques by a supplier of technologies for urban water management, leading to the development of insights and guidance on the adoption of such tools, presented in the context of a number of practical case studies. The paper finds that CFD methods offer genuine opportunities and can yield direct tangible benefits. However, this is reliant on organisations having a realistic understanding of what such approaches can offer, their limitations, and also having an appreciation of the long-term commitment that is required to achieve maximum value.

1 INTRODUCTION

The current global focus on water management and sustainability is driving the use of increasingly advanced, computer-based, design and analysis (including simulation) techniques within the water sector, of which the realisable benefits and associated risks are often unknown. Understanding the investments and resources required to integrate a new tool/technique into a development or analysis process greatly reduces the risk involved and allows the user to make informed judgments on the practicability of adopting such techniques.

The use of the most advanced of these techniques, including simulation tools, has become common within many engineering and scientific arenas, although most are evident within the 'high-technology' industries, for example aerospace and automotive, where investments in such methods are justified by potential significant returns. However, with increasing demands for efficiency and performance improvements in the water sector coupled with developments in computational systems and software, the scope to attain benefits through the use of these methods in this sector has emerged (Faram & Harwood, 2000; Harwood, 2006).

As the automotive and aerospace industries are often regarded as 'high-technology', the water industry in contrast may be perceived as being 'low-technology' and perhaps even 'crude', although the problems presented are often equally challenging when compared on a technical complexity or analytical basis. These problems often require the balancing of a combination of operational variables, for example flow capacity, water quality, system/maintenance cost and system volume, which standard techniques are unable to accomplish. Thus it will be necessary to embrace new analytical and design techniques if the demands of the water industry are to be met.

Computational fluid dynamics (CFD) is a software-based application of numerical methods that allows the prediction of fluid flow fields through the computational solution of the fundamental governing fluid dynamic equations relating to continuity, momentum and energy. Water management processes generally involve: flows in channels/pipes; the transport or separation of slurries, sediments or particulates; mixing in contact tanks for coagulation, flocculation or disinfection; multiphase flows, such as those found in aeration and dissolved air floatation (DAF) systems; and a range of thermodynamic processes associated with mechanical, chemical or bacterial stages in the treatment systems. CFD provides insights into fluid systems without the need (or with reduced need) for physical experimentation, and is particularly useful where environmental conditions or scale restrict physical observations. Nisipeanu (2000) observes "The potential applications for CFD within the water industry are too numerous to list", but the applications encompass all of the scenarios presented above, plus many more.

CFD is a flexible tool that can be used to simulate systems in a number of ways, ranging from three-dimensional highly-complex 'precision' models to two-dimensional rudimentary/simplistic investigations. However, resource investment and risk magnitude is generally proportional to model complexity (Figure 1) which often limits complex, speculative models to academic or long-term/fundamental research based environments. This said, some industrial sectors have been known to pioneer new approaches in CFD due to the specific nature and requirements of their business.

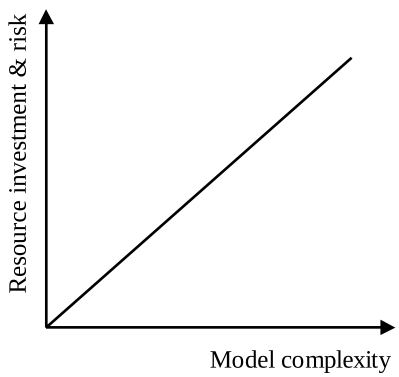

Figure 1: The general relationship between CFD model complexity and resource investment/risk.

Compared to other Computer Aided Engineering (CAE)/numerical tools, CFD can be considered to be one of the more challenging to adopt, requiring greater resource requirements and a high level of commitment from the outset. Subsequently there are often mixed views on the benefits of such techniques. With regard to this, and remaining pertinent to this day, is Bradshaw's comment "the best modern methods allow almost all flows to be calculated to higher accuracy than the best informed guess, which means that the methods are genuinely useful even if they cannot replace experiments" (Bradshaw, 1987).

This paper reviews the usage history of CFD within Hydro International plc, a leading developer and supplier of technologies for water management, with the aim to provide insight and guidance on the adoption and application of CFD for industrial benefit.

2 THE HISTORY OF CFD IN HYDRO INTERNATIONAL

Hydro International is a small to medium sized enterprise (SME) with a reputation for supplying innovative solutions for the management of water and wastewater. It has more than a decade of experience working with CFD, making it one of the first companies within its sector to adopt such tools. Over the years the company's relationship with CFD has been through a number of phases, with challenges experienced early in the adoption process, nearly causing its rejection altogether.

Hydro International's history with CFD started in 1995 with the purchase of a UNIX workstation and Fluent CFD license. This equated to a total investment of a little over £50,000, which, at the time, was considered a high-risk outlay and with expected further costs of several thousand pounds per year to maintain the system. With no previous CFD experience, few measurable benefits were realised at this time, as staff underwent training. Two years later the situation remained much the same as the company went through a difficult trading period leading to significant restructuring. Technical staff had, in the event, struggled to get to grips with the 'new' technology and there had been a reversion to the more familiar experimental approaches to product development. Confidence in the value of CFD at that time was low, however the company embarked on a collaborative effort whereby a PhD student at the University of Sheffield utilised the company's CFD equipment for their doctorial research work (Harwood, 1998).

In 1998, CFD expertise was brought into the company through recruitment of a trained fluids engineer, and the challenge was set to restore the CFD system and endeavour to derive benefits from its use. This was a challenging phase for CFD within the company due to the complications associated with over a year of neglect to the hardware and software, and a climate of scepticism that CFD could deliver tangible benefits. Despite these initial difficulties the challenge was taken up. Whilst it took a number of years to fully rectify the position, CFD is now a fully integrated tool within the development, design and analysis cycle, with clear return on investments being realised, and general acknowledgement relating to the benefit of CFD throughout all levels of the company. This is evidenced by the range of publications that have been produced from the work (Egarr et al. 2005; Faram & Andoh, 1999, 2000; Faram & Harwood, 2000, 2002, 2003; Faram et al. 2004). From this history it can be seen that the initial phases of adopting CFD are critical to its future success within an organisation, and therefore the future of commercial CFD itself. It is believed by the authors that the conveyance of knowledge and experience relating to the adoption and application of CFD will promote its usage within the water and water-related sectors, leading to advancements in all associated technologies.

3 ADOPTING CFD

3.1 *Investing in CFD*

The smallest investment in CFD can represent a significant expense for an SME, therefore a total cost analysis, considering all factors, should be undertaken before embarking on any long-term commitment. The relative cost of CFD software and its hardware requirements have reduced dramatically over the past decade, with the cheapest commercial packages now costing as little as £5,000 (including hardware). This relates to approximately 7% of the initial investment made by Hydro International in 1995 (taking into account the retail price index history). However, for a 'top-end' commercial code based system, software and hardware investments can be in the region of £15,000 per year for a single-seat license, depending on the hardware/software specifications and operating system.

It should also be noted that there are a number of open source or community maintained CFD codes and utilities available, often free of charge or at a significantly reduced cost. An example of this is OpenFOAM, the most commonly used open source CFD code (Weller et al. 1998), distributed freely under the GNU General Public License. These options are valid considerations for some organisations, but are generally more complex in terms of their usage, and thus require a greater level of understanding and ability. These codes may therefore not be appropriate for commercial/industrial use, being most appropriate for use in academia.

Assessing past CFD investments on cost alone provides only a limited basis for comparison, as the computational capacity of the average CPU (measured in millions of instructions per second) has increased by approximately fifty-fold in the last decade. Additionally, advancements in CFD techniques and software have improved the usability and simplified many processes involved with model generation and setup. More efficient solvers have also helped to cut simulation times. The end result of this is that CFD is much more approachable, requiring relatively less resources than ten years ago. This said, there are still many factors that need to be considered when taking such steps in order to minimise the risk, which may still be considered as significant.

3.2 *Familiarisation*

From experience, it is the authors' opinion that the largest significant factor affecting the adoption and use of CFD within most organisations is the level and availability of in-house expertise. From the outset, when attempting to integrate CFD into a new environment where no prior expertise is held, there will be large requirements on user time in relation to familiarisation, training and experimentation, during which no real measurable benefits may be produced. This phase is likely to last for a period of several months while users become competent in usage of the software and understanding of the principles involved. This familiarisation phase can also be a substantial cost relating to training, CFD system time and lost personnel time. In many cases, it can be more efficient to recruit experienced CFD staff.

3.3 *Establishment*

After users have become familiar with the basic usage of the CFD techniques and the system, a phase of procedural developments, sensitivity analysis and validation programmes are likely to be required. This involves: establishing the feasible application areas relating to the organisations business; experimentation with modelling parameters to establish the result's variability ('sensitivity analysis'); and physical testing to provide data against which model predictions may be validated.

This phase of CFD usage will vary depending on the application area and model complexity, but is also likely to account for a significant proportion of the time relating to the integration of CFD into an organisation. If application areas are changed considerably this process will be repeated and may become a regular occurrence in each development cycle of a new product or service.

3.4 *Delivering results and advancing techniques*

Once the foundation for performing reliable simulations and delivering beneficial results is in place, the adoption of CFD into an organisation can be considered to be complete, with standard modelling practices being performed. This is the first stage in which real benefits are likely to be delivered, helping to build confidence and demand for CFD throughout the company.

As demand grows there will often be periods when the requirements for CFD analysis will outweigh the system capabilities, user availability or the user's technical abilities. The system's capabilities are easily upgradeable if current technological advancements and financial resources permit, however user-related requirements are often the greatest challenge. The value of a user in relation to their experience will often dictate the CFD resources available to them. This relationship often dictates that only one or two members of staff become experienced users, who are then relied upon to maximise returns on the CFD investment, preventing advancement of other employees. Though it can be beneficial to train 'technician' staff to perform day-to-day or routine modelling work, thus allowing more experienced users to further their technical knowledge and develop new or improved modelling methodologies.

4 BENEFITS OF CFD?

As with all development and analysis programmes there will be short- and long-term objectives, and the way in which CFD is used will vary greatly depending on these objectives. From the author's perspective it is useful to separate these short- and long-term cycles, and consider how CFD may provide outputs for each to assess its value.

4.1 *Short-term focus investigations*

Short-term focus investigations are considered to involve models requiring in the region of minutes to one week to process. This type of model is generally concerned with establishing indicative results between a range of design configurations or product concepts to act as a decision support tool. For such investigations the model may be simplified in relation to the physical system to give an increase in model turn-over.

Short-term focus investigations may also include product and project support functions, which may involve: providing evidence of operating phenomena and performance; comparisons against existing systems; and analysis of abnormal or specific operating conditions. Investigations into abnormal or specific phenomena can also lead to the initiation of long-term programmes.

4.2 *Long-term focus investigations*

Long-term focus investigations can be considered to last in the region of several weeks to many years. These are generally aimed at providing quantitative results relating to complex processes or phenomena. These investigations are often considered high-risk from an industrial perspective as they also require extensive validation and sensitivity analyses.

It is rare that such investigations are carried out within an industrial company, especially an SME. In the case of Hydro International, some of the more complex studies, in particular, cases where code functionality is either being pushed to the limits or the work is essentially 'experimental' or research orientated, academic collaborations have been established. This allows the continuation of advanced investigations with minimised risk due to the expertise and resources provided by the academic partner. Academia and the CFD industry also benefit from such collaborations due to the funding and research that is driven by the company's interests.

The outcomes of these partnerships often results in material for technical publications and marketing literature, which benefits the industrial communities and helps promote the company's image and commitment to its field.

5 CASE STUDIES

5.1 *Design of a sediment separator for stormwater flows*

In one of Hydro International's most recent developments, short-term focus CFD analysis was utilised to assist in the design of a stormwater sediment interceptor device. During the development cycle CFD was used to analyse a series of design prototypes. This was performed by simulating the range of prototypes using a standardised approach in order to provide comparative results. Once flow patterns were established, a series of simulated sediment particles were seeded into the incoming flow and the removal efficiency of each prototype evaluated. This technique was developed by Faram & Harwood (2003) and has become standard practice within the company for assessing the performance of separation devices. A number of automation scripts have also been created to assist this approach; controlling the model configuration and sediment seeding parameters, providing improved model turn-over and optimum use of CFD system time. This allows CFD performance analyses to be carried out day and night, unaided. Several staff have been trained in the use of these scripts, thus allowing more advanced users the ability to focus on future developments or the analysis of more demanding systems.

Figure 2 illustrates the graphical outputs for stages of refinement in the design evolution (from left to right). Figure 3 shows the removal efficiency predictions for the initial concept and final product design, highlighting the improvement CFD provided in this case. From this project it was established that the model turn-over was less than one week and at a cost of 20% of what physical prototyping would have required (Andoh, 2006). This case demonstrates the benefits that CFD can deliver when used in a strategic, experienced and established fashion.

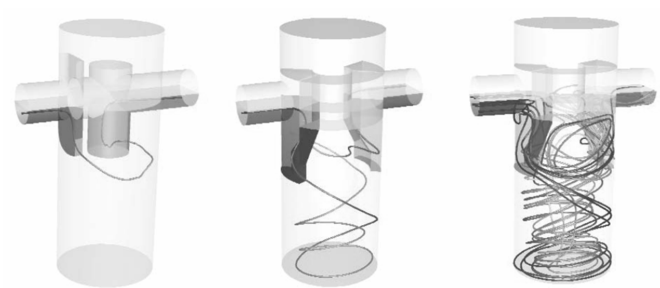

Figure 2: Graphical outputs from CFD for stages of refinement in the design evolution of a stormwater sedimentation system (Andoh, 2006).

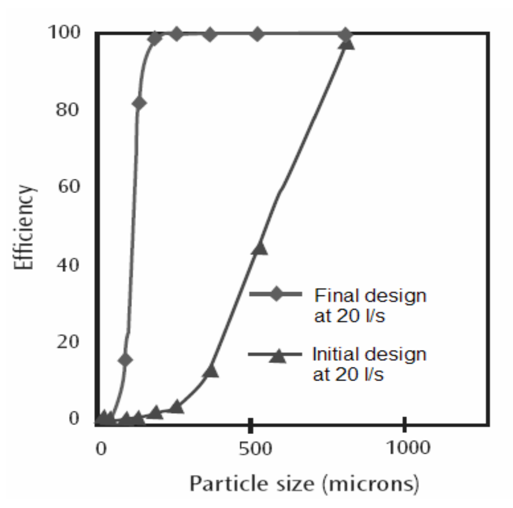

Figure 3: Prediction of the particle removal efficiency of different configurations of stormwater sedimentation chamber using CFD.

5.2 *Assessment of a modular block stormwater storage system*

This case concerns the short-term focus analysis of a patent-protected feature relating to the operation of one of Hydro International's products for the below-ground storage of stormwater, with the aim of demonstrating its functionality. The patented feature in concern was a perforated under pipe that runs the length of the storage volume and prevents the introduction of sediments and other debris into the storage volume. By seeding the inlet flow with sediments in a similar fashion to that outlined in Section 5.1, identical systems with and without the under pipe were investigated (Faram et al. 2004). Figure 4 illustrates the results of the comparison, which provides powerful evidence in favour of the protected design element.

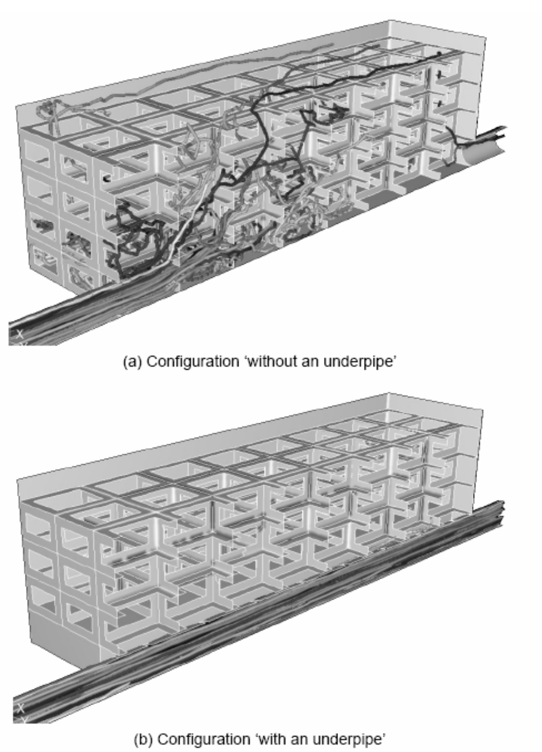

Figure 4: Predictions of sediment particle trajectories in stormwater storage chambers with and without an under-pipe (Faram et al. 2004).

5.3 *Investigations into hydrodynamic separation principles and their use as contact chambers for high-rate disinfection processes*

Through a PhD collaborative project with Cardiff University, a series of studies were conducted with the aim of evaluating fluidic systems for water-environmental applications. As a result of this, many insights were gained into specific phenomena relating to the behaviour of a range of Hydro International's products. A non-exhaustive list detailing areas of knowledge gained from the collaboration is given below (Egarr, 2005).

- Particle mechanics and rheology
- Residence time and its prediction for complex systems
- Further insights into CFD usage and its appropriate configuration in investigating specific phenomena
- Laboratory and analytical techniques
- Predictive techniques for hydrodynamic separation.
- Chemical disinfection.
- Comparative and predictive studies of several separation and disinfection devices (illustrated in Figure 5).

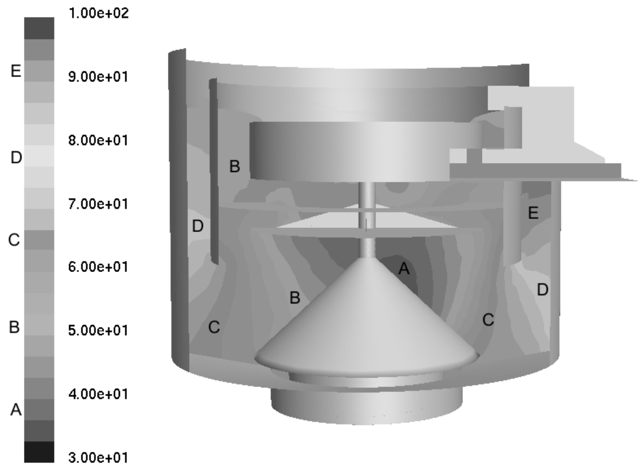

Figure 5: Outputs from CFD work to investigate the disinfection contacting performance of a hydrodynamic vortex separator (Egarr, 2005).

Through this experience, the company has embarked on a series of new product development programmes and has improved knowledge and support for existing systems. The project also provided the material for several technical publications and the incentive to embark on future collaborations. This work has also produced outputs that have been used for technical marketing purposes by Hydro International and by the CFD software vendor, further encouraging the use of CFD for water-related applications.

6 MODELLING FOR SUCCESS

Although the use of CFD can sometimes become overwhelming during the initial adoption stages, there are several key points to remember when seeking to gain value from CFD. The first of these points is potentially the most critical, and this is understanding what CFD can and cannot accomplish. This will be related to the capabilities of the CFD system used and also to those of the operator. Like any other CAE tool, CFD has its place. Applying it to inappropriate situations will produce results of minimal benefit and will waste valuable resources.

Planning CFD is also an important consideration, and links back to understanding the capabilities/limitations of CFD. At the start of every modelling programme consideration should be given to establish the objectives of the programme and the desired outputs. This is acknowledged as being a fundamental stage in ensuring that benefits are produced from any 'information technology' associated investment (Ward & Peppard, 2002). Focusing on the output of CFD will also assist the user in building an appropriate modelling methodology, improving the validity of results and possibly streamlining the modelling process.

With new users, there is always the temptation to overcomplicate modelling scenarios in an attempt to give 'accurate results'. Consequentially, this often has the opposite effect, with a large number of model variables causing fluctuating or inaccurate results. Overly complex models are also significantly more computationally expensive, requiring greater systems resources and longer processing times. Experienced CFD users will usually simplify the model with regard to its focus, removing any unnecessary parameters that may affect accuracy or stability. A prime example of this is a common practice among CFD users where water surfaces are replaced by frictionless solid boundaries (Faram & Harwood, 2003; Greene et al. 2002; Stovin & Saul, 2000 and Ta & Brignal, 1998). By performing this simplification, demanding multi-phase simulations can be avoided for large stable air-water interfaces (water surfaces). Einstein's famous quote of "make everything as simple a possible, but not simpler" should be a guiding principle for most CFD users.

At the end of each modelling program the results should be carefully scrutinised and for new investigations, comprising of extensive validations and sensitivity analyses. It is always important to remember that CFD only has the capacity to approximate physical systems and many assumptions are made in this process. Box (1979) states "all models are wrong, some models are useful" in relation to scientific model building. This highlights the important fact that CFD is not an infallible tool and should always be treated with a measure of healthy caution.

7 PRACTICAL INSIGHTS

Over the years, the CFD users within Hydro International have developed a balanced approach to the application of CFD. Users have learnt to maximise the benefits from any outcomes that CFD investigations may provide and have overcome any issues faced. In reality, CFD is a very demanding tool and can require constant user commitments for long periods of time. User availability is often limited due to normal everyday work commitments, especially in an SME. Although with effective planning, CFD can run continuously day and night to maximise its usage and returns; this is particularly true for large models that run for a period of days or weeks.

As with any technical subject or system, the single most important factor in gaining benefits from CFD is building experience. As user experience grows, modelling procedures are developed, thus creating further demand on CFD resources and validation studies, to the point that user input is constantly required. At this point automation techniques and new modelling approaches are likely to be established reducing user input and allowing less experienced users to carry out everyday modelling. This can further increase demand on CFD resources, maximising returns and CFD's subsequent value. This process will repeat with each new modelling procedure or advancement, and so the risk associated with the use of CFD will reach a limiting fluctuating state, as illustrated in Figure 6. Once the CFD environment has reached this final phase it is likely that the value connected with the use of CFD will greatly outweigh any costs and demands, although analysing the intangible cost benefits may be difficult.

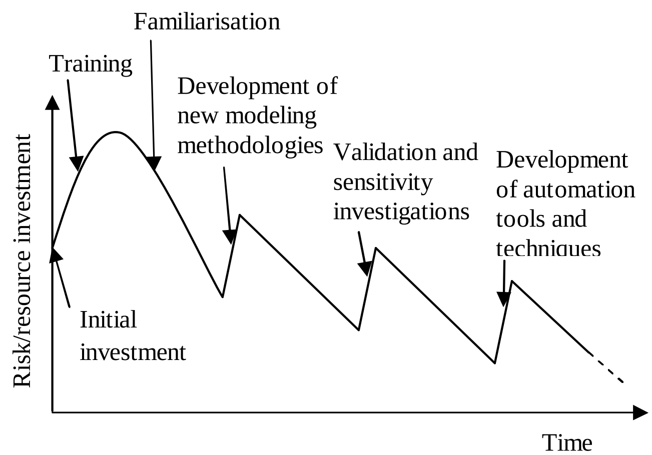

Figure 6: Speculated risk and resource investment profile over the adoption cycle of CFD facilities.

Academic partnerships present a low-risk alternative to performing in-house detailed investigations and provide a suitable access route for industrial or commercial bodies wishing to experiment with the value of CFD. It is believed that the future advancements in CFD will focus on its industry-specific accessibility and automation, to allow even greater benefits to be delivered. These advancements are likely to be performed by academic or larger industrial institutions due to the long-term commitment and resources required.

8 CONCLUSIONS

- The demand for innovation in response to the current climate of interest in water-environmental issues has lead to increased use of advanced computer-based simulation techniques in process and product design investigations. This has been assisted in recent years with the information technology revolution that now allows these techniques to be practically and economically applied in most industrial sectors.
- CFD techniques have become increasingly applied in the water sector, presenting opportunities for the development, analysis and improvement of water management systems.
- Through the personal experiences of the authors over the past decade, it has been found that the adoption of CFD fluid flow simulation techniques can deliver tangible benefits in industrial product development and verification, as evidenced in the presented case examples.
- The adoption of CFD techniques can represent a significant investment and therefore risk to many smaller companies. However, this paper finds that these risks can be minimised through having a realistic understanding of what such approaches can offer, their limitations, and also through appreciating that dedication and long-term commitment will be required in order to fully exploit the opportunities on offer.

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