2004

CFD for Positive Displacement Compressors

B. G. Shiva Prasad
New York

CFD FOR POSITIVE DISPLACEMENT COMPRESSORS

B. G. SHIVA PRASAD
Painted Post, New York, USA
(E-mail: shivaprasad@asme.org)

ABSTRACT

CFD has become a buzz word in all sectors and many industries, while the positive displacement compressor industries are rather slow in embracing it. The paper examines whether it is because positive displacement compressors were considered as basically thermodynamic devices or due to the inherent challenges for application. The paper discusses the need for CFD and it's current status in general, and with reference to positive displacement compressors in particular. The benefits and risks involved in using CFD are also presented.

1. INTRODUCTION

It should not surprise any one why Computational Fluid Dynamics (CFD) is becoming a buzz word in all industries. The simple reason being that fluids pervade the universe, which encompass the natural as well as the artificial environment. Hence to create any new device, one should be able to understand how the fluid environment affects the device in terms of forces, moments, energy loss, etc. and conversely how the device affects the fluid behavior and changes its state and dynamics in order to produce the required operational result. To generate the above information, one could either resort to calculation or experimentation and measurement. Until about 2 decades ago, computation of fluid flows was considered a luxury meant only for the privileged few working in areas of rocket science. The rapid growth in computational science and technology is gradually making it available to all areas of technology. Hence industries who were relying on cut and try methods and experimentation are trying to catch up with the CFD storm to leap frog over competitors, who can neither afford nor have yet seen the benefit of jumping in to the storm.

This paper examines the need for CFD as far as positive displacement compressors are concerned, assesses the general status of CFD application and discusses the benefits and problems/risks involved in using CFD in the positive displacement compressor industries.

In the author's view, positive displacement compressor technology has been very slow in catching the CFD bandwagon, particularly considering the fact that CFD started with rocket science, and the counterpart dynamic compressors and pumps used extensively in aerospace industries were the first to embrace CFD. The author attributes this to the fact that unlike dynamic compressors, positive displacement compressors have been considered as mainly thermodynamic devices and the havoc caused by fluid dynamics in destroying the efficiency has started gaining attention only in the recent past due to the pressing need for making these machines more energy efficient and reliable, and hence there was no enthusiasm for thinking about CFD. The paper also discusses in detail that CFD is not a magic wand and a quick fix to solve all fluid dynamic problems, because CFD itself is in its infancy as far as computing complex flows as found in positive displacement compressors are concerned. At the same time due to the lack of better tools including experimentation, which is not only equally difficult for application to positive displacement compressors, but also becoming increasingly expensive, CFD might turn out to be the only savior for improving the performance of compressors.

Application of CFD to dynamic compressors started about 3 decades ago, while it is just about a decade old as far as positive displacement compressors are concerned. It can also be evidenced by the fact that while papers in the dynamic compressor area have virtually flooded the journals/conference proceedings, there are only a countable few relating to positive displacement compressors. Rodgers & Wagner (1990) were one of the first few to apply CFD for a positive displacement compressor to understand the loss mechanisms in the discharge process of a scroll compressor. They made a quasi steady assumption basing it on the fact that the scroll velocity was only 10% of the gas velocity. They reported a good agreement between their CFD results and the dye flow visualization experiments. Jiang and Tiow (1997) studied the 3D flow and heat transfer inside the Scroll compression volumes by developing a sliding and moving grid to represent the unsteady and varying nature of the compression volume. de Bernardi (2000) demonstrated the usefulness of CFD in the development phase by using it to help design the lubrication pump for a scroll compressor without the need for experimentation. Lenz and Cooksey (1994) applied CFD for a rolling piston compressor to optimize the discharge port geometry for reducing the discharge as well as the re-expansion losses. Sullivan and Harte (1995) demonstrated the use of entropy production rate computation for identifying the loss mechanisms and estimating the losses in the suction flow path of a rolling piston compressor. Cyklis (1994), Fagotti and Possamai (2000), and Ottitsch (2000) demonstrated CFD application for reciprocating compressor valve design optimization, while Chikurde et al. (2002) used CFD for studying the thermal flow field outside the main flow path but inside the shell of a hermetic reciprocating compressor. For the screw compressor, Kovacevic et al. (2000 and 2002) developed a CAD - CCM (Computational Continuum Mechanics) interface program for generating the grid and analyzed it's flow field considering fluid-structure interaction effects using a commercial solver, and found good agreement in the prediction of performance parameters with experimental data. It is important to note that although the above investigations have demonstrated the usefulness of CFD for analysis and design optimization, the validations could only be done at a cursory level and that too to justify the design optimization intent. In fact, as discussed later, the question of rigorous validation of the code is a big issue not only for CFD application to positive displacement compressors but to all other areas and is being debated in the CFD community (see for example: Marvin, 1995 and Shiva Prasad, 2004).

2. NEED FOR CFD

2.1 Need for Fluid Mechanics

To understand the need for CFD one should start understanding the need for fluid mechanics. The need for fluid mechanics itself was a debatable issue until about 2 to 3 decades back and there was little push to understand the part played by fluid mechanics in reducing the efficiency of positive displacement compressors. The basic reason for this complacency was the fact that positive displacement compressors were considered as purely thermodynamic devices, since they were directly changing the state of the gas from a lower to a higher pressure by physically displacing the gas in to smaller and smaller volumes. The process of compression appears to be a purely thermodynamic process of changing its state, which was an apparent justification made for such a consideration. However, as the inefficiency could not be explained by thermodynamic reasons and the need for improving efficiency became a higher priority, one had to start probing the causes for inefficiency. It does not need much effort to find out that the actual P-V card differs from the ideal thermodynamic cycle and the deviation of each of the thermodynamic processes of suction, compression, discharge and expansion from the ideal are attributable to fluid dynamic causes. For example the most important process of compression is affected by leakage, unsteady heat transfer across the boundaries of the compression volume and some viscous shear at the boundaries as well as fluid mixing. Both leakage and heat transfer occur in both directions across the boundaries of the compression volume. Gas leaks out of the compression volume in to the suction or lower pressure chamber while at the same time it could also enter the compression volume from the higher pressure or discharge chamber. The extent of leakage depends on the areas of the gaps or clearances across the moving and the fixed boundaries in most of the positive displacement compressors, and the resistance offered by the leakage path to the leakage flow. In some positive displacement compressors like the reciprocating type, such leakage could occur across the suction and discharge valves also, as they too form part of the compression volume boundary. The heat transfer is unsteady and changes direction since the gas temperature inside the compression volume changes in magnitude during the compression process. There will be a flow of heat in to the compression volume during the beginning of the compression process as long as the gas temperature remains less than the temperature of the material constituting the boundary and a flow away from the compression volume during the latter part of the compression process, when the gas temperature exceeds the temperature of the bounding surface. Both convection and conduction are responsible for this heat transfer loss which ends up in heating the suction gas and reducing the volumetric efficiency. In screw compressors, part of the unwanted heat generated during the compression process is removed by injecting a liquid which sometimes serves to lubricate the sliding screw surfaces also, thus reducing the frictional loss.

One does not have to look at the distortion of the P-V card and understand its cause for inferring fluid mechanics as the underlying reason for the losses. In fact, one cannot fail to conclude the existence of large fluid dynamic losses by looking at the rough and tortuous path with drastic cross sectional variations along the fluid volume from suction to discharge. This is true for all types of positive displacement compressors and more so for the ones which use valves and introduce large area changes in the flow path. Fluid mechanics also plays a role in the interaction with mechanical elements like the valve plates/rings in reciprocating compressor, the scrolls in scroll compressor, vanes in sliding vane compressor, etc., to induce vibration, noise, unsteady loading, etc., all of them again resulting in performance penalties. Similarly fluid mechanics is also known to interact with the piping acoustics leading to piping pulsation - a source of vibration and noise.

Fluid mechanics plays a role not only in determining the performance of positive displacement compressors but also in their design analysis, operation, reliability as well as cost. Although more and more attention is being gradually paid to reducing fluid dynamic losses by removing obvious obstructions and unwanted area changes in the flow path, the concept of streamlining and gradual diffusion applied in dynamic compressor design has not yet spread to positive displacement compressor design. Similarly, the practice of optimization of dynamic compressor flow path component design considering fluid dynamic performance to be of major importance has not yet pervaded the field of positive displacement compressors. In fact, unlike in dynamic compressors, aerodynamic design of the flow path has not become an important design activity/function. Similarly a separate fluid dynamic analysis activity does not exist in the case of positive displacement compressors. Most of the fluid dynamic losses are modeled as orifice type losses. It is very clear from the discussions above that fluid dynamics should play an important role in performance estimation. The reliability both in terms of reliability of performance as well as operational reliability are also affected by fluid mechanics. In reciprocating, sliding vane and other compressors with moving valve elements, breakage of valve elements due to slamming on the seat or guard caused by fluid dynamic related mechanisms like valve stiction or reverse flow, etc. are quite common. Also, overheating caused failure either due to leakage or improper heat removal by the coolant due to formation of stagnation zones in the coolant loop are again attributable to fluid dynamic causes. Such stagnation zones in the coolant flow path could occur not only in and around the compression volumes of screw and reciprocating compressors but also inside bearings. An aerodynamically designed flow path is likely to increase the manufacturing cost, while the operational cost might reduce due to improved reliability. All the above facts clearly identify the importance of fluid mechanics although its acceptance has been rather slow.

2.2 Need for CFD

The above section clearly established the importance of fluid mechanics in all aspects of positive displacement compressor technology. Since performance and reliability are influenced by fluid mechanics, it is very important to understand and estimate the energy lost as the fluid flows through the compressor from the suction flange to the discharge flange and at the same time estimate the static and dynamic loads including any unsteady loading experienced by components through which the flow occurs. The energy loss is important for compressor performance estimation and component performance assessment for help in design, while the loading information is required for structural design of the components. Such information could either be obtained by computation or measurement. Both detailed flow field computation, which goes by the name of CFD or measurement are difficult and are in various stages of development. Flow field measurements in positive displacement compressors are limited to measurement of static pressure and temperature only and that too are possible only at some locations. Not only are other flow field measurements of total pressure or velocity extremely difficult to make inside compressors but are also highly expensive in time and cost and hence the preferred choice would be computation. Most of the present day routine computations are limited to calculation of the actual thermodynamic cycle by integrating the one dimensional conservation equations for mass, momentum and energy together with the equation of state along with empirical models of lumped losses accounting for the inefficiency attributable to fluid-thermal causes. However, as described earlier, the fluid flow is far from one dimensional and even unsteady to be more exact. Hence, if one wants to improve the performance prediction and design, CFD appears to be not only a logical but a practical alternative.

3. STATUS Of CFD

In the last 2 decades CFD has spread from aerospace to not only other industries but also to non industrial sectors like medicine, sports, etc. This rapid growth was funneled by the phenomenal growth in computer speed and memory and the simultaneous decrease in cost. The huge success in aerospace development which is to a large extent attributable to CFD also spurred this further spread to other industries and sectors. It is interesting to note that CFD also owes its roots to dynamic compressors, the counterpart of positive displacement compressors. It has been extensively applied and reasonably validated for application to dynamic compressors, due to the fact that dynamic compressors and pumps are used in airplane and rocket propulsion systems. Surprisingly, CFD has also gained popularity in positive displacement machinery, viz. - the IC engines, while it is still at an infancy as far as positive displacement compressors are concerned. One cannot perhaps attribute this to the fact that IC engines are a part of the popular transportation system, since positive displacement compressors are also used extensively in the energy sector, and are a part of many of the heat pump systems used in day-to-day life. On the other hand, one could perhaps attribute it to the understanding of the importance of fluid mechanics in achieving efficient combustion together with the appreciation of its importance in controlling the distortions in the thermodynamic cycle for improving the overall efficiency of the power production process. On the other hand, as mentioned earlier, positive displacement compressors have been considered incorrectly according to the author as purely thermodynamic devices, which explains not only the lack of attention to fluid mechanics but also to CFD. How ever, the recent push towards energy efficiency has created a grater need and hence increased interest in understanding the role of fluid mechanics in reducing the efficiency. Unfortunately as stated earlier, experimentation is not only becoming expensive in terms of time and cost, but cannot also be easily carried out in positive displacement compressors due to reasons of complexity in geometry (particularly the fact that the compression volume is non stationary and unsteady), harshness of environment and inaccessibility. These facts are driving researchers and technologists towards CFD which has started drawing increasing attention, particularly since the latter part of the past decade.

The slow spread of CFD can also be attributed to the challenges presented for computation by the complex internal flows which occur inside positive displacement compressors. Traditional methods used in CFD requires dividing the fluid volume in to smaller and smaller volumes in order to integrate the conservation equations in space and time, step by step across the entire volume. This time consuming process of grid generation is one of the road blocks for CFD application to any field and has become so for positive displacement compressors also. CFD code developers have paid attention only in the recent past for developing moving and sliding grids which are required to model the motion and variations in compression volume as well as other volumes formed by moving surfaces like valve elements. Also, unlike the dynamic compressor analysts, who have enjoyed for a long time the luxury of pre-processors and in fact complete codes tuned for modeling those geometries, nothing is available for positive displacement compressor analysts, other than some extensions of geometry modeling and grid generation methodology developed for IC engines. Stosic and his coworkers (2000, 2002) at the City College of London lead the first devoted effort towards developing a grid generator for screw compressor geometry. They have successfully used their grid generator and computed the screw compressor flow field considering even the fluid-structure interaction effects. Generating grids using the available general purpose grid generators becomes a highly time expensive proposition for industries to embrace. Positive displacement compressor industries are waiting for development of user friendly pre and post processors for application to their use. The draw back for the progress appears to be the large number of types of positive displacement compressors with widely varying geometry and operational features which already exist in the market place with further addition taking place on a regular basis. Each one of them requires a separate pre-processor module and their development require enormous effort with little pay back. On the other hand, in the dynamic compressor area, axial and centrifugal are the two main types and the market potential and pay back for software developers is highly attractive.

Grid generation is one area where analysts have to spend time for generating a good grid. Solution of the conservation equations is not transparent to the analyst and the time involved depends on the solver, computer speed, and the total number of elements constituting the grid. Computational speed has increased enormously, which was earlier identified as an important contributor to the rapid growth of CFD and faster algorithms have been developed to further reduce the solution time. The grid size and total number of elements is determined by the flow field itself. The highest frequency, the ratio of the largest to the smallest flow length scale and the physical size of the model itself are factors which affect the grid size and the total number of elements. Unfortunately for positive displacement compressors with small clearances, valve openings and compression volumes, and a large range of flow scales starting from these small sizes to the large compression volumes at the beginning of the compression stroke, the number of elements required is huge. The computer hardware advancements are gradually overcoming these draw backs. However in the author's view, the problem of solution accuracy still persists. The flow complexities of three dimensionality, compressibility, asymmetry, anisotropy, unsteadiness, etc., in addition to the wide variations in spatial and temporal scales of interest makes one wonder whether any turbulence model developed for simple laboratory flows could ever pass a rigorous validation test for it to become acceptable for application to positive displacement compressors. Still, for the lack of a better alternative and keeping the basic engineering needs of the designer in mind, one could use the available turbulence models for obtaining the gross performance and flow parameters. One could argue these results to be much better than those obtained by 1D modeling, where the assumptions are introduced at the gross flow (i.e., at a much higher level than in turbulence modeling) level itself. How ever, to gain confidence in the results, validation is required. Although for the reasons stated earlier, detailed flow field measurements are difficult to make, measurement of gross parameters like static pressure, temperature could be made for comparison with the P-V and the V-T traces over a cycle. One could also measure and check the total pressures at some locations. To sum up, validation and credibility of CFD results are perhaps a much bigger issue for positive displacement compressors than other areas due to the mere fact that application of CFD has just started.

4. BENEFITS & RISKS

Direct, evolutionary design involves analysis and performance estimation even before prototyping. As mentioned above, 1D modeling and analysis is too simplistic for the flow occurring inside positive displacement compressors and CFD has a better potential for predicting such flows. 1D analysis with lumped loss modeling is good as long as the empirical loss models have been generated by testing and they are not used for predicting new designs which go far beyond the old family. If the latter becomes a necessity, then CFD has a much better chance of success in those cases. CFD is known to be a very economical tool for optimization during the evolutionary design process. It not only helps in evolving new designs in unexplored territory but also saves time and cost in optimizing, testing and validating them. The other major advantage of CFD is its ability to provide detailed information over the complete flow field, which is not only difficult to generate by testing, but even if it were possible, would be exorbitantly expensive in time and cost. Such information would not only help understand the flow mechanisms generating the losses but also help in optimizing the designs to prevent or modify them. Further, with proper validation, it can not only be used for identifying and estimating the extent of high loss regions by applying the entropy production rate method (see Sullivan and Harte, 1995) but can also be used for estimating component losses like the valve loss, cylinder passage loss, piston ring leakage loss in reciprocating compressors; suction and discharge passage loss in scroll compressors, etc. Also, with proper validation, it can replace the experimentation required for predicting the equivalent flow area of valves (see Ottitsch, 2000). In essence, CFD could become a very useful tool for analysis as well as design for improving performance, reliability and saving cost.

One cannot embrace CFD assuming that it is a tested and proven tool. Despite its wide acceptance and application, it has neither undergone rigorous testing nor is it proven to scientific standards for practical application even for external flows in aerospace systems or internal flows in turbomachinery - the two areas where it found its roots. Although, the basic modeling and algorithm development inevitably started in universities, it reached the end users in industries through code developers and it satisfied them as a good engineering tool for developing their products and met their engineering objectives and standards. The basic yardstick used is whether it gives them engineering answers for helping in the design and development process while reducing the process cost. Such yardsticks are not helpful even to ascertain whether it delivers satisfactory results to another industry developing a similar product. Hence there is always a risk of using CFD not just for the fear of producing bad designs or incorrect analysis, but also for being questioned about the veracity of designs based on CFD, unless one has gone through the process of validation. Even with such a validation, one will always have to critically examine the results before accepting them, since the process involves assumptions in every step of the way starting from modeling the geometry to represent the true hardware to using the right mesh size, interface type, boundary conditions, initial conditions and solution control parameters. The risk of using CFD as a black box for design and analysis and paying penalty is perhaps greater than the risk of using empirically based codes, since empirical tools will have some experimental and experience basis and less holes to be poked, while CFD being a widely known tool, in addition to questions about its specific use for the product in question, one will be faced with a barrage of questions about the general problems regarding CFD. There is also a risk of casual and inexperienced users using it as a black box and putting too much faith in the results of CFD based on its popularity and the appealing nature of the results. Further, it may also lead to complacency about the need for validation. CFD enjoys the immunity from indictment in any accidents, even if it is catastrophic, since it is easy to blame the material or the design of the structure which displays a physical evidence of destruction rather than CFD, which might not have predicted the unsteady loads properly but which becomes difficult to prove, since such evidence of overloading will not exist. Although this appears to be a benefit for the CFD user rather than a disadvantage, it is definitely a disadvantage to the CFD community in not being able to understand its deficiency and improve the technology to correct the problems.

5. CONCLUSIONS

The drive for energy efficiency has driven away the inhibition for using fluid mechanics for improving the performance prediction of positive displacement compressors, thus paving the way for CFD to gain entry in to the field. CFD has a very good potential to advance the development of positive displacement compressors by contributing to all aspects of its technology, viz., design, development, analysis, reliability and cost. However, CFD is still an art and has not become a mature science. Not only are its solvers not yet capable of handling the complex flow field inside positive displacement compressors, their preprocessors are also not ready to handle the complex geometry and operational features. Hence, even though CFD offers important benefits, it can not be used as a black box and is not a magic wand and one should trust and use it, only after verification and validation. However, for the lack of a better tool, it is important to start joining the bandwagon with other industries and start using CFD for analysis and development as it needs a considerable time and effort to build the trust before considering using it as a tool for design.

REFERENCES

Chikurde, R. C., Loganathan, E., Dandekar, D. P., Manivasagam, S., 2002, Thermal Mapping of Hermetically Sealed Compressors Using Computational Fluid Dynamics Technique, *Int. Compressor Engrg. Conf. at Purdue*, Paper No. C6-4.

Cycklis, P., 1994, CFD Simulation of the Flow through Reciprocating Compressor Self-acting Valves, *Int. Compressor Engrg. Conf. at Purdue*, pp. 427-432.

de Bernardi, j., 2000, CFD Simulation of a Scroll Compressor Oil Pumping System, *Int. Compressor Engrg. Conf. at Purdue*, pp. 707-713.

Fagotti, F., Possamai, F. C., 2000, Using Computational Fluid Dynamics as a Compressor Design Tool, *Int. Compressor Engrg. Conf. at Purdue*, pp. 137-144.

Kovacevic, A., Stosic, N., Smith, I. K., 2000, Grid Aspects of Screw Compressor Flow Calculations, *Proc. of 2000 ASME Int. Mech. Engrg. Congress,* Orlando, pp. 79-82.

Kovacevic, A., Stosic, N., Smith, I. K., 2002, Numerical Simulation of Fluid Flow and Solid Structure in Screw Compressors, *Proc. of 2002 ASME Int. Mech. Engrg. Congress,* New Orleans, Paper No. IMECE2002-33367.

Lenz, J. R., Cooksey, E. A., 1994, Application of Computational Fluid Dynamics to Compressor Efficiency Improvement, 1994, *Int. Compressor Engrg. Conf. at Purdue*, pp. 441-446.

Marvin, J. G., 1995, Perspectives on Computational Fluid Dynamics Validation, *AIAA Jour.*, Vol. 33, No. 10, pp. 1778-1787.

Ottitsch, F., 2000, CFD A Viable Engineering Tool for Compressor Valve Design or Just a Toy?, *Int. Compressor Engrg. Conf. at Purdue*, pp. 423-428.

Rodgers, R. J., Wagner, T. C., 1990, Scroll Compressor Flow Modeling; Experimental and Computational Investigation, *Int. Compressor Engrg. Conf. at Purdue*, pp. 206-215.

Shiva Prasad, B. G., 2004, Benchmarking in CFD, Paper Accepted for Publication in the *2004 ASME Heat Transfer/Fluids Engineering Summer Conference, Charlotte, NC,* Paper No. HT-FED2004-56746.

Sullivan, T. J., Harte, S. A., 1995, CFD Simulation and Entropy Production-based Loss Analysis on an A/C Compressor Suction Flow-path, *Proc. of 1995 ASME Int. Mech. Engrg. Congress, San Francisco, CA*, AES-Vol. 34.

Jiang, Z., Tiow, O. K., 1997, Prediction of Flow and Heat Transfer within a Scroll Compressor Working Chamber, *Proc. of 1997 ASME Int. Mech. Engrg. Congress, Dallas, TX.*