Multi-phase CFD study of a reciprocating gas compressor with liquid slug ingestion

Contents

The thermo-fluid-dynamics phenomena that occur in a cycle of a reciprocating compressor, and in particular the pressure loss through automatic valves, ducts and manifolds, cannot be investigated and detected easily with a traditional experimental approach. The investigation is even more difficult when it comes to biphasic fluids. They can be studied only by means of advanced simulation techniques.

The effects of a liquid slug ingestion in a reciprocating compressor cylinder for gaseous hydrocarbons have been analyzed using Multi-phase CFD with the goal to calculate the pressure distribution on the piston. It has been demonstrated that the pressure forces can reach high values which may cause structural failure in the crank mechanism.
The study was conducted using the software ANSYS FSI simulating the behavior of a mixture of gaseous and liquid hydrocarbons during the delivery of the crank end of a cylinder of a horizontal reciprocating compressor.

Introduction

The reciprocating compressor is a machine which consists primarily of: (see Figure 1):

- Frame
- Crankshaft
- Connecting rod
- Crosshead
- Rod
- Piston
- Cylinder
- Automatic valves
- Ancillary equipment (coolers, separators, dampers bottles etc)

Figure 1 illustrates an horizontal balanced opposed reciprocating compressor of the same type as the one considered in the analysis.

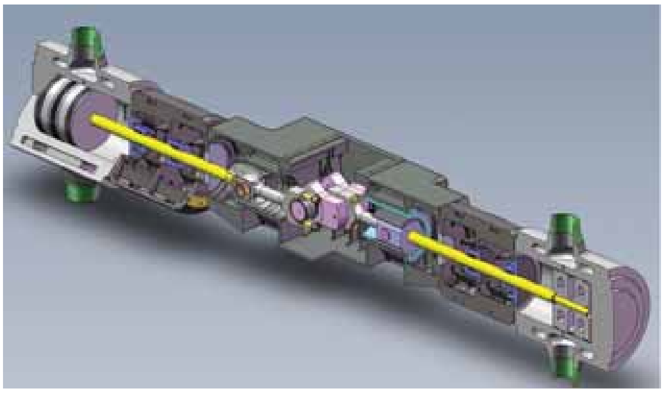

Figure 1: Schematic picture of a typical horizontal reciprocating compressor

The type of fluid handled by this kind of machine has to be strictly limited to gas, under no circumstances can there be a liquid fraction. This is also explicitly stated in the standards API618 - Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services - Ref [1] governing the design and the operation of these machines.
Moreover, the compressor is typically inserted into a complex plant, which contains equipment, such as reactors, heat exchangers, separators, etc., while it is very common that the type of fluid treated represents a mixture of hydrocarbons. The hydrocarbons may have a rather high temperature, dew point (condensation), while the complexity of the plant, most often installed in open fields, can lead to uncontrolled cooling of pipes as well as to defects in the operation of the liquid fraction separators.
The particular case described here is about the remote possibility of the machine being in the abnormal condition of liquid ingestion.

Purpose of the study

The phenomenon of liquid inlet is as dangerous as insidious: beyond the extreme cases (continuous suction of only liquid with consequent stoppage or sudden destruction of the compressor), sporadic incidents frequently occur in which one or more cylinders suck important liquid fractions for a certain number of cycles. The study showed that the damage resulting from these events may seriously affect the life and safety of the machine, even if at the time of the event, no apparent damage was observed.
The purpose of this article is the simulation of the arrival of fluid at the intake of the crank end of a double acting cylinder of a reciprocating compressor, to determine the intensity of the forces that are generated in the various machine components, with the purpose of investigating whether they may be responsible for damages, and if so, for what kind of damages.

Examined case

The machine used is described below:

- 4 double acting cylinders
- Power 400 kWatt
- Rotation speed 500 RPM
- Automatic discs valves
- Rated inlet pressure 15 bara
- Rated Delivery pressure 21.2 bara

This is a refinery compressor and the fluid handled is a mixture of hydrocarbons with the following characteristics:
<u>gas phase:</u>

- Molecular weight 11.7

liquid phase:

- Density 600 [kg/m^3]
- Viscosity 2.7e-4 [kg / (m s)]
- Specific heat 2238.0 [J / (kg ° K)]
- Thermal conductivity 0.1344 [W / (m ° K)]

Normal operation (gas)

Figure 2 shows the pattern of pressures in the cycle when the machine is in normal running condition, handling gas. For example, for the crank end and starting from Bottom Dead Center, the steps of:

- Clearance volume expansion
- Suction up to Top Dead Center (the pressure inside the cylinder is below the nominal value of suction pressure due to the valve pressure drop)
- Compression
- Delivery (the pressure inside the cylinder rises beyond the nominal value of the discharge pressure of the pressure drop due to valves)

The forces on the crank mechanism depend, other conditions remaining equal, on the maximum discharge pressure.

Operation in abnormal conditions (liquid ingestion)

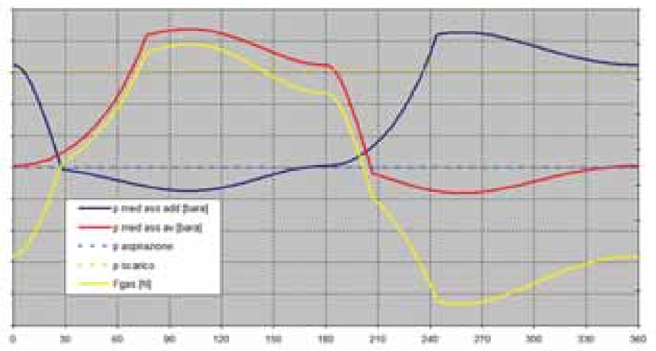

Figure 2: Evolution of pressure in a cylinder of a reciprocating compressor

If a cylinder is beginning to ingest a certain amount of liquid at every turn, one will find an increasing fraction of liquid in the cylinder during the subsequent phases of compression, in a way that is not simple nor unique to represent.

The diagrams of the discharge pressure will change dramatically and, as described in detail below, different models have been implemented (analytic one-dimensional) that allow to estimate the liquid fraction inside the cylinder, the trends of pressure and the peak value reached. These models are highly sensitive to the values of pressure and the loss factor assigned to the valve cylinder – the valve port system.

Importance of transients

The pressure loss factors of valves are known with good approximation for the normal operation with gas in steady state (usually are found experimentally on test benches in steady state conditions). In the conditions that we want to investigate (liquid ingestion), one faces an operation with a gas-liquid mixture fractions variable which is not predictable by analytical calculation methods. Of particular importantance is the influence of the opening and closure transient of valves, covering a rate close to 35% of the duration of the whole delivery phase.

All this shows how inadequate it is to perform calculations using constant parameters, that consider a steady flow in such a transient phenomenon.

Innovative method for and approach to the problem

We have observed how the nature of the physical phenomenon does not allow us to investigate and obtain sufficiently accurate results with a one-dimensional approach.

Also a CFD two-dimensional approach is not adequate to the problem complexity as it not possible to identify symmetry conditions.

The only adequate method to quantitatively analyze what happens in the cylinder and through the valve is a threedimensional CFD simulation.

Moreover, to achieve the aim of investigating the actions on the most critical parts of the machine, one needs to simulate the fluid dynamic transients and dynamic structural constraints that determine the concentrations, flows and pressure behavior not only in terms of mean values but point by point and at every instant of time.

The new method of investigation develops in the following steps:

- 1D gas (single phase)
- 3D CFX Direct Analysis (mobile mesh, rigid valve rings with rigid translational motion, single phase).
- Validation of the model by means of absorbed power measurement.
- 1D analysis multi phase involving more consecutives cycles
- Definition of the initial conditions of the subsequent 3D analysis
- 3D CFX Direct Analysis (movable meshes, rigid valve rings with rigid traslation motion, multi phase).

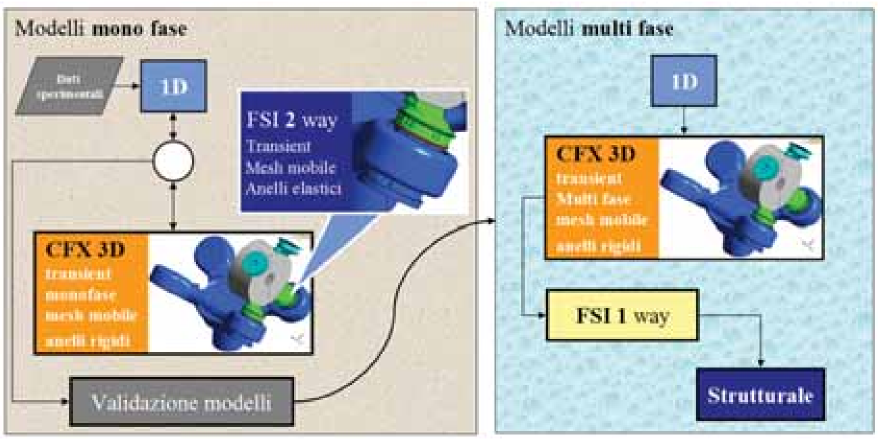

Figure 3

- Valuation of the importance of the transient phase during the cycle (single phase).
- Transient analysis by means of FSI 2Way.

Models of analysis for the method development
One-dimensional method description

The one-dimensional calculation (Visual Basic code implemented in Excel) considers the crank end of a reciprocating compressor cylinder. Its purpose is to analyze the abnormal operating conditions in which the pumping cylinder ends, starting from the rated operating conditions with only gas, performing cycles with liquid, resulting in pressure peaks during the compression phase (see Figure 4).
The thermodynamic transformation is considered isentropic.
The sheet contains all the input data for the calculations, including the value of the step of calculation in terms of fractions of crank angle.
The calculations related to the cycle start from the suction phase (BDC for the crank end and UDC for the head end) with a zero amount of liquid inside the cylinder, and gas at delivery pressure. Then, a suction phase of only one type of liquid mixed with a residual gas in the clearance volume of

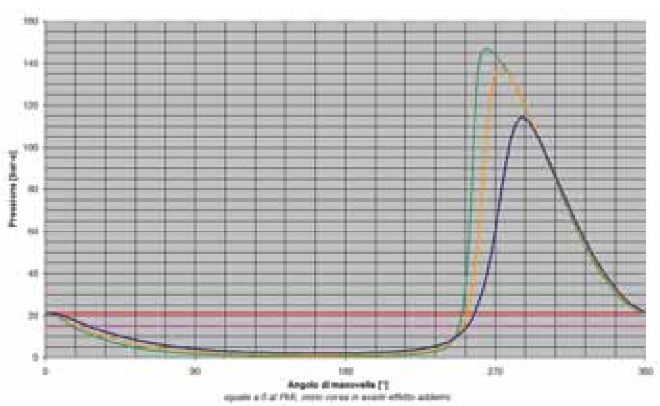

Figure 4

the cylinder is simulated. The harmful gas-liquid mixture will be compressed and discharged through the delivery valves.
The final quantities of gas and liquid in the clearance volume conditions at the end of each cycle, are taken as initial conditions for the next cycle. The volume of fluid inside the cylinder increases during every subsequent cycle, since only liquid is sucked, and a mixture of gas and liquid is discharged.

3D CFD Model

The thermo – fluid dynamic analysis was conducted using a fluid dynamic model that reproduces a symmetrical portion of the cylinder crank end and covers, by symmetry, one delivery valve and an one inlet valve (Figure 5).
The fluid analysis was performed in transient and turbulent condition, under the assumption of compressible mono or multiphase flow, and using deformable mesh calculation.
The deformation of the 3D domain changes the configuration of the cylinder, whose volume is reduced with a time law imposed by the law of motion of the piston, and changes the configuration of the valve also, whose rings are moving according to fluid dynamic forces acting on them.
The mobile surfaces are those of the piston and valve rings within the valve. The simulation of opening and closure of the valve rings in CFX is obtained by solving the equation of the motion of the rings, treated as not deformable and with only one degree of freedom (translational).
n the motion calculation, the dynamic forces acting on the rings, the characteristics of inertia and the forces due to springs, have been taken into account. At this stage, it has been considered acceptable to consider the rings as infinitely rigid and to calculate a movement of pure translation, since the rings are fully open in the zone of the cycle where the maximum pressure occurs. This was the main objective of this study, and it is even more correct in the operation with liquid + gas (multiphase).

The software used for analysis are:

- ANSYS ICEM-CFD for the generation of geometry and mesh calculation
- ANSYS-CFX for fluid analysis

At the end of a functional construction of the calculation mesh and the definition of 3D regions with flexible walls, 4 different fluid domains were defined.
In the various regions of fluid, meshes with hexahedrical elements are realized, which allow better quality control of the mesh during the motion of the piston and rings, while tetrahedraical prism mesh are used in those regions where deformations of the geometry do not occur: in fact a tetrahedrical mesh is able to better describe in detail the geometric complexity of the areas close to the valve.
The flow was considered transitional and turbulent (k-? turbulence model standard).
The resolution of the equation of total energy allowed to take into account the conditions of compressible flow.
Not being negligible the action of gravity of the liquid phase, also the gravity effect was taken into account.

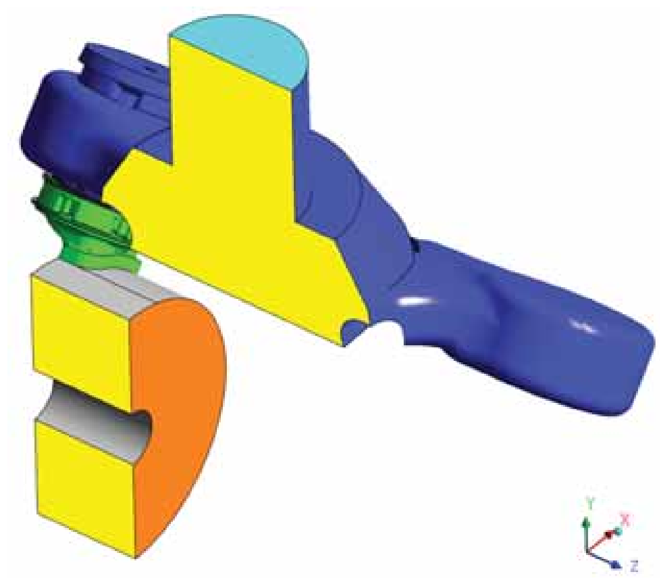

Figure 5

In the multi-phase analysis, a homogeneous model with regard to speed, temperature and turbulence was used.
The use of a multi-phase model involves the solution of transport equation for the variable "volume fraction". This variable allows to describe the distribution of two phases in the system.
The use of a homogeneous multi-phase model on a particular variable assumes that the two phases share the same field for the variable in question.
With reference to the speed, this means that at every point of the domain, gas and liquid are characterized by the same velocity vector.
The basis of this model is the assumption that the exchange of the momentum, energy and turbulence between the phases are sufficiently high to ensure that the two phases are found everywhere in equilibrium and therefore share the same fields.
Under this hypothesis, it is possible to solve the transport equations using the properties of "bulk" that are calculated locally on the basis of physical properties and depending on the volume fractions of the two phases.
Other parameters for the analysis are listed below:

- In the Multiphase analysis, liquid + gas are considered with immutable percentages, without the effects of evaporation or condensation.
- Mechanical parts are considered as undeformable (the profile of motion of the piston is known, and its deformation does not influence significantly the fluid dynamic field).
- The load of each valve spring of the rings (a total of 18 springs, the outer ring 8, 6 on the central, 4 on the inside with k = 3.06 N / mm housed in the holes of the counterseat) is 3.672 N
- To the rings of the discharge valve the only degree of freedom of axial translation was assigned
- The initial conditions for the 3D analyses are derived from the one-dimensional analysis method at the time of the compression start.

Method application

First, it was necessary to develop a model and to validate it. Since for gas operation values, the factors of compressor valves loss in steady state conditions are available, a single-phase one-dimensional model to evaluate the pressure curve of suction and delivery, was first implemented.
Then, the delivery phase of the cylinder has been simulated in a 3D model CFX mono phase.
The pressure loss factor was verified, calculated with CFX, where the rings are fully open. It was in agreement with experimental values, while in the opening and closing transients, they were much higher.
For this reason, the absorbed power has been evaluated. Again the result was in agreement with the experimental data.
The model, thus validated, was used again to re-run the same cycle of analysis with the multiphase fluid.
Given the characteristics of the plant where the machine operates, the pattern of arrival of the liquid in the cylinder tests was the suction of fluid from the cylinder with liquid for two subsequent cycles. With these assumptions and through the one-dimensional model, the complete first and second cycle (intake and discharge) have been simulated - Starting from the UDC, to determine at the start of the delivery phase of the third round, the fraction of liquid and the values of pressure and temperature in the cylinder. The latter are then to be used as the initial conditions for the subsequent analysis CFX 3D.
The pressure field calculated by CFX Multiphase analysis was then imported into 3D structural analysis to assess the state of stress on the machine-induced pressure peak.

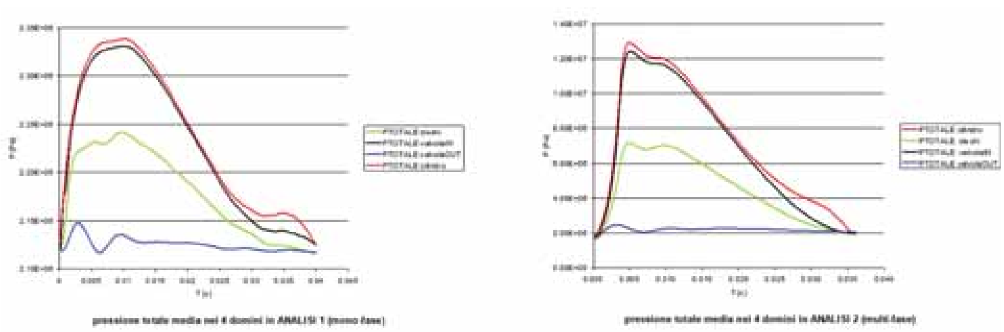

Figure 6

Results

The maximum pressure inside the cylinder which was obtained from the CFX 3D multiphase analysis is 125 bara, against the nominal 21.2 (see Figure 6)
This value of pressure is certainly likely to cause structural damages of the machine even after a few (3-5) cycles of abnormal operation, which can significantly reduce the operational life of the machine.
The 1 Way FSI analysis have permitted to find that the values of forces on the cranks mechanism can reach levels that would cause irreversible damages.

Model FSI 2Way

The simulation permits to analyze the interaction among the fluid and the structure considering the various aspects related to the elastic deformability and the inertia of the components. The pressure profile on the interface surface fluid / solid defines for each time instant the force field that stresses each valve ring determining the deformation profile and the motion condition.
The valve rings have all the possible degrees of freedom, rotational and translational, and have been added the limit in axial displacement due to the valve seat and counter seat.
The analysis has been performed with gas because this is the situation relevant to the normal operation of the machine, and has confirmed, moreover, that the valve rings are a

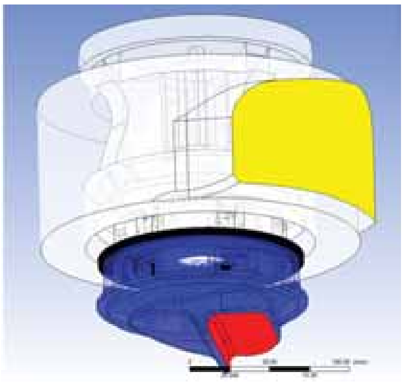

Figure 7

critical component of the machine. Also in normal conditions, the analysis has been limited to a portion of the domains, to the valve portion actually, to reduce the calculating time.

The boundary conditions for inlet and outlet have been assigned through the profiles of pressure calculated from the CFX 3D mono phase analysis on the surfaces involved (highlighted in red and yellow in figure 7).
For the valve rings, the model “transient structural” has been implemented in ANSYS, and preload springs and gravity have been considered.
Hexahedral mesh has been used for the rings in ANSYS.
To the surfaces of the rings in ANSYS CFX the boundary condition "mesh motion" with the "ANSYS Multifield” option was assigned, while the outer surfaces of the rings have been assigned the "Fluid Solid Interface” status.

Additional considerations: analysis of valve opening and closing transients
At this point, the duration of the transients of the opening and closure of the valve rings in the cycle with gas has been estimated. We could ascertain that they cover a total of about 35% of the length of the discharge (see Figure 8).
The approximation of considering the valve rings as rigid bodies and assign them a movement of pure translation is adequate to evaluate the peak pressure, but it is not acceptable for the evaluation of the opening and closing transient phase.
Given that this is more than 1 / 3 the length of the delivery in which the system cannot be considered in regimen, the phenomenon of transient is analyzed in more detail by means of FSI analysis using 2Way simulation to assess more thoroughly the fluid dynamic (pressure) and mechanical (deformation of the disks, the stress states induced, vibration, shock, etc.) phenomena.
Figure 9 shows a short sequence of the transient opening and closure of the valve rings in the cycle with gas, starting from a steady state. The sequence is in an enhanced deformation scale (100:1) in order to better evaluate the deformation and vibration affecting the rings and the different dynamic behavior of the single ring with respect to each other. Note that at the end of the whole cycle the rings do not reach a new steady state, however, they are vibrating at the beginning of the following opening cycle.

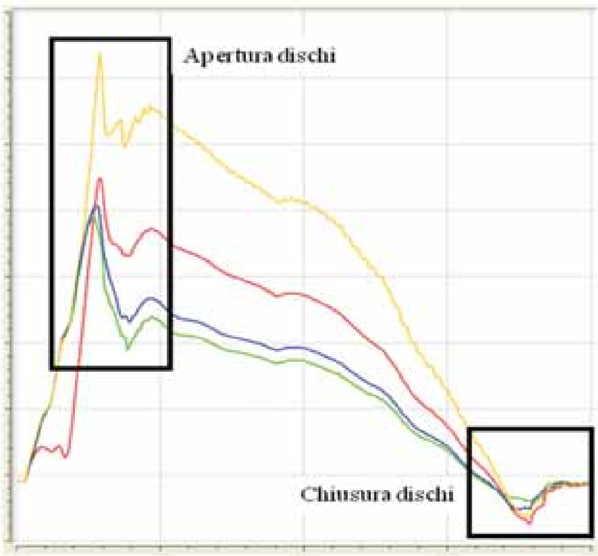

Figure 8

Conclusions
With the help of the multi-phase analysis in the CFX environment, we could demonstrate the hidden dangers of a gas compressor which operates only a few cycles with ingestion of liquid.
The introduction of approximations utilized in the CFX 3D analysis (such as, for example, the rigid motion of the valve rings or their consideration as rigid bodies) is permitted when the aim is evaluating the overall performance of the plant, but becomes unacceptable when seeking to investigate the functioning of specific organs of the machine.
The subsequent analysis 2Way FSI focused on automatic valves allowed to characterize the actual behavior of the moving parts (valve rings) of the valve itself in the transient opening and closing, highlighting the influence of motion of the valve rings on the progress of local pressures and strains and pressures on the valve rings during each cycle.
We wish to stress that it would be very difficult to demonstrate these elastodynamics phenomena with other analytical methods or experimentally, and that the findings represent accurately the criticality of operating these components.

The validity of the method to analyze transient phenomena characterized by highly dynamic transients has been proved, where traditional experimental techniques or analytical calculation can hardly provide adequate information.

We believe that these models can be effectively extended, providing many benefits, to investigate similar phenomena involving the interaction between fluids and flexible mobile facilities in other areas. In particular, the use of this method may allow the optimization of fluid dynamic profiles of the valve zone of cylinder compressors with a good chance of reducing related energy consumptions.

References
[1] API618 - Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services

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