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# Modular tool for the simulation of compressor trains for oil and gas applications

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## Abstract

Recently, in the oil and gas extraction and transportation field, much attention has been paid both to increase efficiency and to reduce the environmental impact of the extraction techniques that, by now, consists mainly on Enhanced Oil Recovery processes based on gas or water injection into the reservoirs. Thus, compressor trains are a crucial part of the overall plant, and they require precise performance estimation during the whole oilfield lifespan, when production rates and compression demands significantly change. For this reason, in compression plant design and in-service behavior prediction, modular simulation codes turns out to be the best choice respect to tools for specific plant configuration, since they provide flexibility without losing accuracy.

In this paper, a new modular tool for compression plant simulation is described; it is based on a wide database of centrifugal compressors and a library of elementary components that can be freely assembled to build any plant's configuration, regardless of its layout. The code's numerical solver is the implementation of a trust-region Gauss-Newton method, called TRESNEI, which possess a larger convergence region than standard Newton methods.

The performance of the code has been tested on two compression train arrangements with both series and parallel-mounted compressors; comparison with the solution of the test cases obtained with a dedicated pre-existing in-house code, shows a good matching between the results. Computational speed and robustness of the new code is also shown.

**Keywords**: Compressor trains; Power plants thermodynamic simulation; Modular codes; Constrained nonlinear systems of equations; Trust-regions methods

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**Nomenclature**

| | |
|---|---|
| $N$ | number of plant's units |
| $N_S$ | number of chemical species |
| $N_M$ | number of mass flow ports |
| $N_W$ | number of mechanical connections |
| $N_Q$ | number of heat flow ports |
| $n_M$ | number of connections between two mass flow nodes |
| $n_W$ | number of connections between two power nodes |
| $n_Q$ | number of connections between two heat flow nodes |
| $N_{BE}$ | number of bond's equations |
| $N_{BC}$ | number of boundary conditions |

## 1. Introduction

The oil and natural gas exploration and production industry is a highly dynamic and still growing sector. Even though, recently, an increased oil supply and a receding demand growth have created a systemic imbalance turned out into a crude oil price fall, there are solid growth prospects for the future [1]; especially for natural gas, global demand is expected to increase as a consequence to pollution reduction policies that force to replace coal-fired electricity with greener energy sources [2].

In order to keep low both energy prices and environmental impact of industrial oil and gas activities, extraction, processing and transportation efficiency has become one of the most important objectives for companies. Used in drilling operations, in many production operations and extensively used in surface transportation via pipelines, compression trains are widespread in the oil and gas sector [3].Many studies pointed out that the largest energy consumption of onshore and offshore plants takes place in the gas compression, reinjection and separation trains, where pressure changes are more significant, both on mature and on early life fields [4, 5, 6, 7]. Clearly, in transportation field, energy required to move oil and gas is provided solely by compression facilities [8].

Enhanced oil recovery methods are widely used as they can increase production of the extraction fields beyond what is typically achievable with conventional recovery techniques, and they mainly consist in gas or water injection into reservoirs; since recovering incremental oil is complex and costly, it becomes convenient only under exacting operating conditions that may differ a lot respect to maximum extraction rate's ones, when conventional techniques are preferred [9]. Compression plants for oil and gas applications are generally designed for near-peak hydrocarbon production of fields, and they become inevitably less performing, beside the normal process of components' ageing, when production rates and operating conditions change [10]. In this respect, conventional designing of compression trains could be very limiting if enhanced oil recovery techniques are to be used throughout extraction fields' production life; the requirement of flexible and efficient compression processes equipment, that can be easily switched, for example, from series to parallel operational mode across its lifespan, has therefore growth significantly over the last years.

These are the reasons why oil and gas companies are always more interested in flexible numerical tool which can quickly and precisely simulate performance ofincreasingly complex compression plants.

## 2. Compressors Modular Tool

In compression plants design and in-service behaviour prediction, short computational time and great accuracy in performance assessment are met with the use of numerical 0/1-D codes. The more traditional dedicated approach, leading to codes that are specifically built around a particular plant configuration with fixed input data or allowing just limited variations of these, have been progressively replaced by the modular one, that can handle general plant's layout and general input data.In this respect, can be underlined the work of Carcasci and Facchini that realized a modular code for applied research [11] that, grown over the years, allows to achieve thermodynamic [12], design and off-design analysis of industrial plants [13, 14]. Other examples of modular tools for plants' performance estimation are, for example, [15, 16, 17].

In this section is provided a brief description of a new modular tool for compression trains simulation, named CMT, Compressors Modular Tool, based on a modular code thoroughly described on a previous work [18].This tool is based on a mathematical solver implementing a trust-region Gauss-Newton method, called TRESNEI [19].

### *2.1 System modeling*

Compression plants, although complex, are generally representable by a combination of a finite number of elementary components such as compressors, heat exchangers, valves, mixers, flanges, etc., connected with each other. With regard to Figure 1 that represents a generic compressor plant and its model, within each element (henceforth named unit), thermodynamic, energetic or chemical transformations of the operational flows (mass, power or heat flows) can take place. Depending on the internal flows, each unit has some inlet and outlet ports which handle the corresponding working flows and generate the system networking; at each unit's port corresponds a node that, in accordance with the passing through operational flow, can be classified as mass, power or heat flow node. Therefore, flows connect the units through nodes.

In every single node, the flow state can be fully determined by the following properties:

- mass flow properties: mass flow rate, chemical compositions (mass/molar fractions of the chemical species) and thermodynamic parameters (pressure, temperature, enthalpy);
- power flow properties: mechanical power and rotational speed (typically the power flows represent shafts);
- heat flow properties: thermal power.

Every unit can be treated as a black-box that represents a particular energetic transformation and links the flow properties of each operational flow between the entry and exit nodes. A unit is also characterized by some typical parameters that affect its performance, as for example efficiency, pressure or heat losses.

In order to model a generic compression train, CMT is thus built around a library of different units, each representing a typical component of compression plant, where all the transformations (thermodynamic transformations, mass and energy flows' continuity) are mathematically described. Solving the plant consists in finding all the flow properties in each node and all the typical parameters of each plant's element. To pursue this issue, some of these properties and typical parameters are known and constitute the boundary conditions of the problem. Notably, in the present modular framework, there is no need to specify which conditions have to be imposed and in which node, provided that there is a sufficient number of independent parameters for the plant's solution. Moreover, it is important to remark that the values of the flow properties should satisfy some bound constraints which are generally specified by the plant designer and guarantee that the computed values have physical meaning, e.g.. trivially, absolute pressure must be nonnegative.

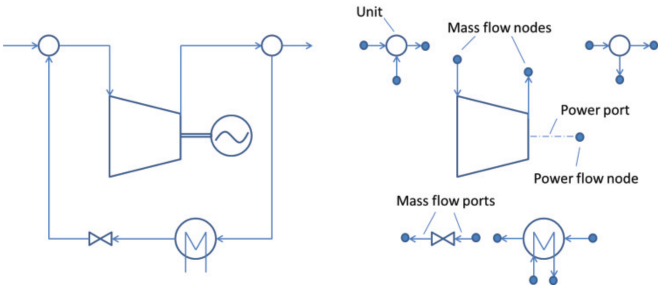

Figure 1: example of a compression plant and its modular model

Physical properties of real gas mixtures have been made available by including an appropriate thermodynamic library, mainly based on the relations of pure fluid and mixtures available in [20] and developed within GE O&G Group. The equation of state used in conducting numerical simulations on the compressor trains, working with a hydrocarbon mixture, is the Benedict-Webb-Rubin-Starling [21].

The whole code has been implemented using the ANSI Fortran 90 standard. Each unit has been developed as an independent subroutine ensuring maximum flexibility of maintenance and upgrade.

### 2.2 Mathematical model overview

Once defined the plant's layout, the physical processes are modeled in mathematical terms. Let a plant be composed by $N$ units with inlet and outlet connections. Let $N_{M,j}$be, for each unit, the number of mass flow ports, where 4 (mass flow rate, pressure, temperature and enthalpy) plus the number of chemical species concentrations, $N_S$,are the unknown terms. Let $N_{W,j}$be the number of mechanical connections, with unknowns mechanical power and rotational speed, and $N_{Q,j}$be the number of heat flow ports, with thermal power as unknown, where the subscript j refers to the j-th unit. These terms represent the problem's unknowns.

Three kinds of governing equations are then necessary to describe the plant: flow continuity equations, bond's equations and boundary conditions.

Continuity equations impose the conservation of flow properties between connected nodes; since the number of flow properties depends on the type of node, let $n_M$ be the number of connections between two mass flow's nodes of different elements and $n_W$ and $n_Q$ be the number of connections between power and heat flow's nodes.

Unit bond's equations describe the physical transformations occurring in each component of the plant (mass balances, energy balances, adiabatic relations for expansion or compression, equations of state, heat exchanges and many other), and are generally nonlinear. They are defined within each unit to characterize its functioning, solet$N_{BE,j}$ denote the number of bond's equation of the j-th unit. Since from bond's equations definition many different types of equation form scan arise (handling and solving these equations require a computational effort that is proportional to the number of different bond's equations types), as accurately described in [18], all the bond's equations have been arranged in four general algebraic forms.

Finally, the last kind of equation is represented by boundary conditions that fix the value of known flow properties in some nodes of the plant and characterize the solution of the problem; let $N_{BC}$ be the number of these boundary conditions.

Summarizing, if the overall number of unknowns (left-hand side) and equations (right-hand side) coincides, i.e.

$$\sum_{j=1}^{N}(4+N_S)N_{M,j}+2N_{W,j}+N_{Q,j}=(4+N_S)n_M+2n_W+n_Q+\sum_{j=1}^{N}N_{BE,j}+N_{BC} \tag{1}$$

then the system of nonlinear equations is squared. Under suitable assumptions on the non linear system, the solutions are locally unique and, imposing reasonable physical bounds on the variables, it is expected to have only one solution. Such a system is solved by TRESNEI (Trust REgion Solver of Nonlinear Equalities and Inequalities); for insights about this solver[18, 19, 22].

Interestingly, this modular approach allows the definition of a fully implicit mathematical model of a plant. Hence, differently from several existing sequential or semi-parallel approaches adopted in dedicated simulators, the nonlinear equations can be solved simultaneously. Advantages of this feature are threefold: the problem setting and the solution is not affected from the ordering of the plant's elements; how and where imposing the boundary conditions of the problem is not relevant; it is possible to set boundary conditions in order to reduce the number of required operational parameters, e.g. efficiency.

In order to solve the nonlinear system of equations, after an appropriate reduction of the system dimension by elimination of dependent variables (like those arising from simple continuity bond's equations and from flow continuity equations), a procedure consisting in two iterative cycles has been set up. In the inner iterative cycle, TRESNEI solves the equations' system through iterative refinements towards a partial solution. In the outer cycle units' subroutines are invoked and, according to the values currently assumed by the physical properties, bond's equations characterizing each unit are set up. After reaching a prescribed accuracy on the physical properties of all the plant's nodes, a suitable solution is found and the plant is solved. For further details on this modeling procedure please refer to [18].

Iterative processes based on Newton's method require an accurate localization of the initial guess since their convergence is strictly influenced by the vicinity of the initial guess to the solution. That is one of the major drawbacks of the use of such methods in modular codes, as the numerical behavior resulting from the modeling of complex plants could generate system's failure in locating the proper root of the problem; this feature is also referred to as local convergence. With a trust-region based solver, such as TRESNEI, selecting an initial hint sufficiently close to the solution is no further necessary. This property, known as global convergence, enhances the robustness of the overall procedure.

## 3. Code's testing on two compression trains

Two real compression trains for oil and gas applications with different layouts have been thermodynamically simulated with CMT. Performance assessment of the new code has been estimated through comparison of the obtained plants' results with those evaluated with a pre-existing in-house dedicated tool, property of GE Oil & Gas.

The test cases represent the same compression plant, a two centrifugal compressors each made of two stages, typically used in Enhanced Oil Recovery operations; the plant is switched from parallel to series operating mode, with the possibility of intercooling when series mode is activated. They are outlined in Figure 2 along with boundary conditions and operating parameters.

These are general configurations usually adopted to avoid efficiency drop of the compression trains due to significant changes in oilfield production rates; in early life of a field, when extraction rates are greater, are required high injection flow rates with relatively low pressure, thus a parallel configuration is preferred. When the amount of extracted oil starts to decrease, is needed a lower quantity of gas but with a higher pressure, then it becomes more convenient to operate the plant in a series configuration, without drastically modify the plant's components themselves.

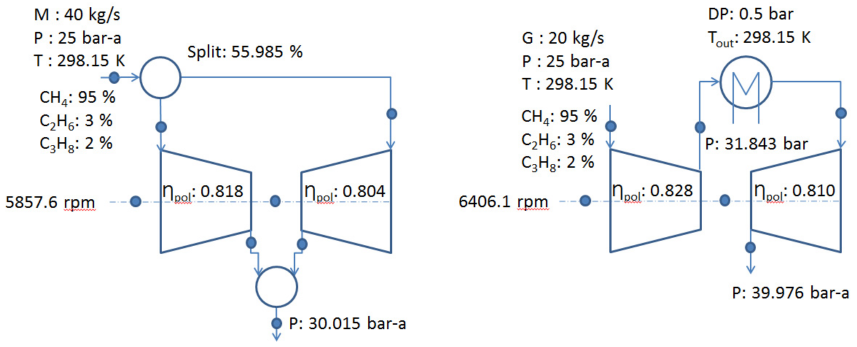

Figure 2: compression plant operating on parallel (layout 1) and series mode (layout 2)

Table1: main results of layout 1

| | | M<br>[kg/s] | P<br>[bar-a] | T<br>[K] | $W_1$<br>[kW] | $W_2$<br>[kW] |
|---|---|---|---|---|---|---|
| **CMT** | in | 40 | 25 | 298.15 | 709.756 | 567.533 |
| | out | 40 | 30.015 | 313.71 | | |
| **GE** | in | 40 | 25 | 298.15 | 709.926 | 567.528 |
| | out | 40 | 30.015 | 313.71 | | |

Table2: main results of layout 2

| | | M<br>[kg/s] | P<br>[bar-a] | T<br>[K] | $W_1$<br>[kW] | $W_2$<br>[kW] |
|---|---|---|---|---|---|---|
| **CMT** | in | 20 | 25 | 298.15 | 834.612 | 847.115 |
| | out | 20 | 39.976 | 319.08 | | |
| **GE** | in | 20 | 25 | 298.15 | 834.551 | 847.204 |
| | out | 20 | 39.976 | 319.08 | | |

Simulations of the two test cases has been carried out with CMT; centrifugal compressors are the same for both layouts, for simplicity in the picture are not represented the two compressors' suction and discharge flanges. Mixer and split are modeled only in parallel functioning while, instead of those two, a cooler is modeled for refrigerating gas between the compressors connected in series. Therefore, layout 1 is made up of 8 elements. Starting from an initial number of 103 bond's equations and 160 unknowns, the mathematical system is reduced to 36 equations in 36 unknowns. Convergence at a precision of $10^{-6}$ is then reached after 4 outer iterations in $4.68\cdot 10^{-2}$ seconds (with an Intel i7-4770 processor). Layout 2 is composed by 7 elements that initially lead to 87 bond's equations and 132 unknowns. After proper simplifications the final mathematical system consists of 28 equations in 28 unknowns. Solution is found after 4 outer iterations in $3.12\cdot 10^{-2}$ seconds.

In Table 1 and Table 2 are summarized, for the two test cases, main problem's results obtained both with CMT and with the GE O&G dedicated tool. These latter are taken as basis for comparison since this dedicated tool have been thoroughly validated over the years through experimental evidence. The plant's sections in which are reported the results are, for layout 1, the inlet of mixer and the outlet of split, and for layout 2, the inlet flange of the first compressor and the outlet flange of the second one.It is possible to outline that the CMT's results match very well those from the dedicated tool. This seems to indicate that the new modular tool is reliable, as the computational effort measured by computational time in seconds provides its efficiency.

## 4. Conclusions

In this paper is presented a new modular tool for compression train simulation. The features guaranteed by simulation modular codes meet the needs of industry for versatile tools for the prediction of lifelong performance of compression plants where "flexibility" is the keyword in the present landscape of the oil and gas sector.

Details on the problem's modeling, mathematical system's generation and numerical solution via an implemented trust-region solver, are given.

The modular tool introduced is capable of simulating any compression plant configuration, as long as all the different kind of plant's elements are present within the component's library implemented into the code. Another advantage of this approach is that the input data, providing they are independent and in sufficient number, are irrespective from a specific fixed set. The mathematical model for the plant's simulation consists of a nonlinear system of equations describing the thermo-fluid dynamics and mechanical processes that take place within the considered elements. Once properly defined, the entire system is simplified by means of elimination of dependent variables and solved iteratively by TRESNEI with a parallel/full implicit mode; the equations are solved simultaneously and an accurate initialization guess is not required to enhance convergence.

The entire program has been developed in Fortran 90 language and its different parts, specially the library's components, has been modeled through independent subroutines allowing maximum flexibility and expandability of the code.

Two real compression trains have been thermodynamically simulated; code's robustness and insensitivity towards initialization values were proven. Comparison with a dedicated in-house code from GE O&G has shown a good agreement between results obtained with the two codes. Further development of the code will include implementation of design and off-design analysis, for stages selection and performance curves estimation respectively.

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