COMPSYS - A SIMULATOR OF GAS COMPRESSION PLANTS

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ABSTRACT

The simulation of large gas compression plants, formed by several serial or parallel machines, such as those used to feed pipelines, distribution networks or storage systems, is becoming of great interest for the solution of the recurrent control problems and for the improvement of system's operating flexibility.

In fact, the relatively high operating flow rates and pressures impose the use of dynamic centrifugal machines which must work within a defined range of the operating diagram, in order to avoid noxious surge phenomena. The plant and its control system perform this task at different levels of intervention, both globally and on the single units, on the plant start up, shut down and/or variations on gas demand (pressure or flow rate). The control functions are many and follow non-linear and complex laws. Thus, it is essential, both during the plant's design, before its installation and in possible refurbishing or upgrade phases, to verify that, during the operating transients, instability and interference phenomena do not occur.

COMPSYS is a simulator of such compression stations, implemented by the author and his collaborators with MATLAB®-SIMULINK®, which allows the analysis of plants configurations and operating transients customisable with flexibility, due to the already developed library of components. This includes models of the compressors and the drivers (electric or turbine), the thermodynamic model of real gases mixtures, of the valves outflow, of the pressure losses and variations propagation in the pipes, the mass and energy balances in the manifolds, the control laws and the load sharing laws among the machines.

This paper describes the most essential aspects and the general architecture of ***COMPSYS***. Some of the functional blocks such as the compressors working maps and the thermodynamic functions are implemented with pre-calculated tables, while other blocks includes functions calculated at each integration step.

Finally, a typical case of simulation and its explanation are illustrated.

1. INTRODUCTION

Gas compression plants which typically feed pipelines, distribution networks or underground storage systems must be controlled in order to achieve both an optimum performance of the whole plant and of its components, and a safe management in every operating condition, transients included. Particularly, it is necessary to avoid surge phenomena, consisting in large and dangerous variations of flow rate and pressure, occurring below 50-70% ca. of the nominal flow rate corresponding to the enthalpy head on the machine.

This aim is important since the plant design phase, to identify its best configuration and to specify and verify both the most suitable control strategy and the requirements on components.

The large compression plants are usually formed by several machines in serial and/or parallel configuration. Sometimes the serial units are connected to the same driver, which can be electric or a turbine (Figs. 1 and 2).

In the simplest case (Fig. 1) the gas flow goes first into a K.O. drum, then through the compressor and a heat exchanger (Cooler). When more serial units are used, this operating path is repeated for each one.

The control system performs different functions, sometimes implemented through independent loops, often co-ordinated by supervising Performance Controller. The basic controls are:

- input and/or output pressure control;
- delivered flow rate control;
- anti-surge control.

For the latter function, two principal recycle loops are considered:

- ***Hot Recycle***, so called because the gas is recycled to the compressor inlet before entering the cooler; this is the first control loop intervening near surge conditions;
- ***Cold Recycle***, which, on the contrary, recycles the gas after the cooler; this control loop operates later, to avoid an excessive gas temperature rise in the machine and the pipes due to a prolonged action of the hot recycle; as shown in Fig. 2, serial units may each have one and/or share a global cold recycle, following the plant design requirements.

Besides the functions mentioned above, the control system also performs:

- the ***Load Sharing*** function, which optimises the plant efficiency, the number of working units and the working point of each unit;
- the control on the start up and shut down sequences of the single units and of the whole plant.

The main purpose of the simulations is in conclusion to verify, with a global approach, the proper and co-ordinated working of all such control functions, in order to achieve not only the right setting of the controllers parameters, but also the correct sizing of the mechanical devices (machines, valves, exchangers, instrumentation), during the different transient and stationary conditions of the plant.

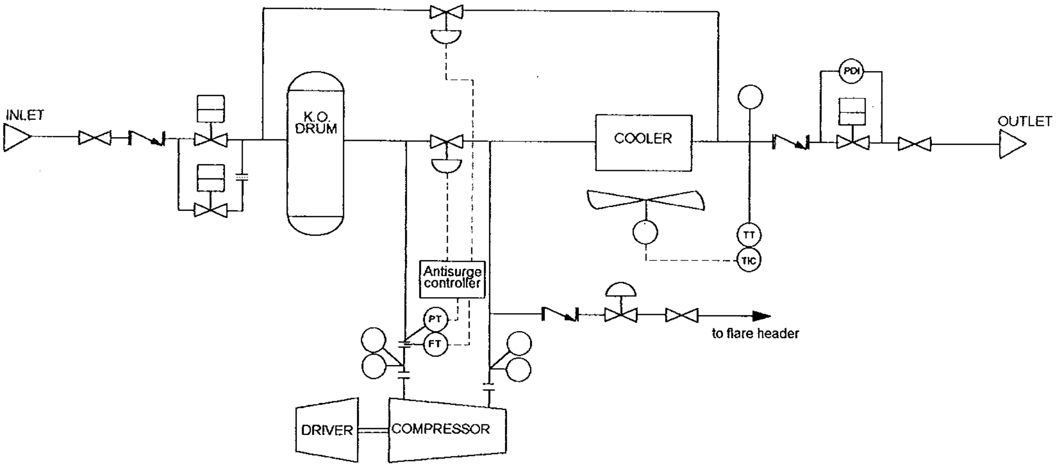

Fig. 1 - Example of a system studied with ***COMPSYS*** - Single machine compression unit.

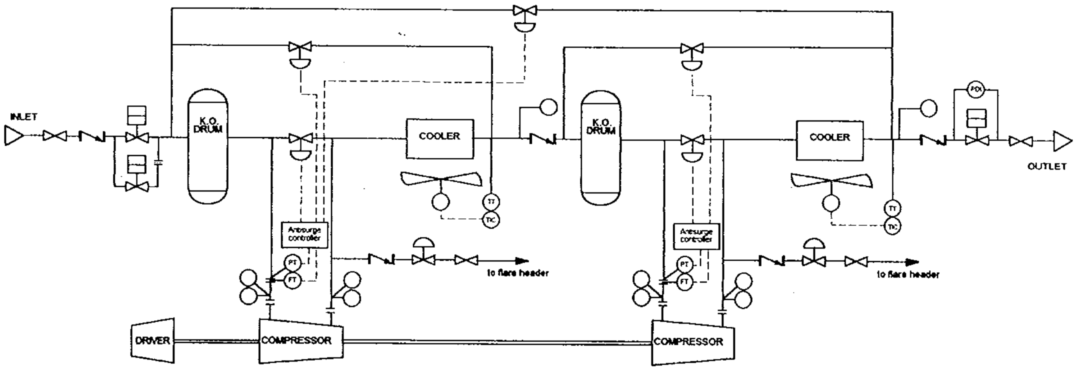

Fig. 2 - Example of a system studied with ***COMPSYS*** - Two serial machines single driver compression unit.

2. BRIEF DESCRIPTION OF THE MODEL

COMPSYS considers the actual non linear behaviour of the system, both during the compressors working and during the operating phases with the machines stopped.

The following subsections illustrate the hypotheses assumed and, qualitatively, the main formulations for the modelling of the main system components.

2.1. Properties of the Fluid

The gas is simulated as a mixture of real gases, with the Benedict-Webb-Rubin-Starling State Equation [3,4], based on the pseudo-critical properties of the mixture as function of its composition, defined in input.

From the state equation, whose values are suitably tabulated in a pre-processing phase, the other subsequent tables are numerically drawn, based on the relevant definitions and thermodynamic equations (Maxwell Equation of Energy):

- the compressibility factor and the relevant partial derivatives, as function of p_r and T_r[1];
- ideal enthalpy and deviation of enthalpy from the ideal one, as function of p_r and T_r ;
- ideal entropy and its deviation from the ideal one, as function of p_r and T_r ;
- temperature and its partial derivatives as function of the pressure and the entropy (Fig. 3).

The transport properties of the fluid are instead calculated and then tabulated basing on the following equations [4]:

- thermal conductivity: Euken Equation for low pressures (dependence on T), corrected for high pressures with the Stiel-Thodos formulation;
- absolute viscosity: Thodos Equation for low pressures (dependence on T), corrected for high pressures with the Reichenberg correlation.

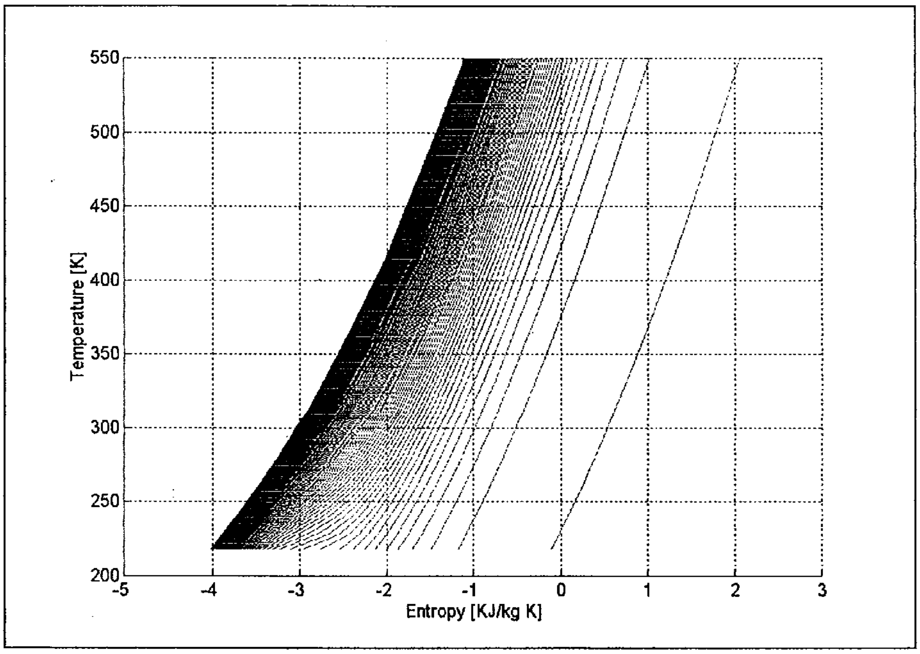

Fig. 3 - Example of state diagram of a mixture of real gases - T-S diagram of natural gas (the resolution of the isobaric curves corresponds to the tabulated function used by ***COMPSYS***)

2.2. Models of the Pipes and the Valves

The plant dynamics is associated to the mass and energy storage inside the manifolds and the buffer volumes, besides to the dynamic change of the rotation speed, of the valves movements and of the control signals. The dynamic bandwidth of these quantities is usually small compared to the acoustic phenomena inside the pipelines, so in the basic version of ***COMPSYS*** the simulated flow conditions in the pipes are:

- subsonic and quasi-stationary[2] for the pipelines; the gas compressibility and the volume of the pipes are suitably taken into account as a lumped capacity placed at one of the pipe ends;
- subsonic or sonic (choked flow) and quasi-stationary for orifices and valves.

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[1] The subscript "r" indicates the reduced quantities: $p_r = p/p_c$ e $T_r = T/T_c$

[2] The flow rate between two sections of a pipe is time by time in equilibrium with the pressure drop, basing on the friction losses equations.

Once the lengths of the pipes become considerable, a dynamic model considering also flow inertia can be used, i.e. a monodimensional finite elements model taking into account the delays in the propagation of the pressure waves, with parameters varying with time (Fig. 4).

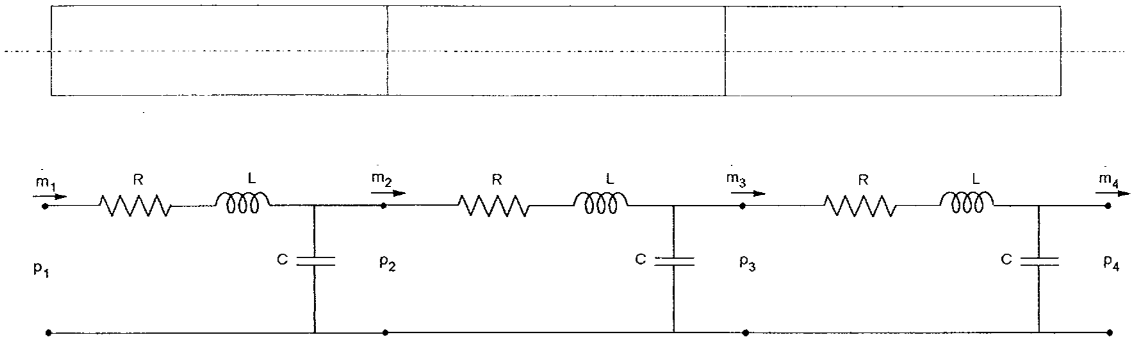


Fig. 4 - Electro-acoustic equivalence of a tube (R and C change non linearly with time, following the instantaneous flow rate and sound speed in that portion of the tube)

The Darcy loss coefficient in the pipes, on which R depends in Fig. 4, is defined by the Moody Equation.

The pipes are considered as adiabatic, or more precisely isenthalpic and non isentropic flow; the thermal exchange can be nevertheless easily implemented in a further extension of ***COMPSYS***.

The curve of the outflow coefficient versus the opening of the valves is described with an arbitrary law, even non-linear, defined as a system input, while the dynamic response of the control actuators is assumed linear, 1st order, with a time constant defined itself as an input, in addition to the other characteristics. The opening of the on/off valves is instead given by a pre-defined time law.

2.3. The Compressors

The compressors are simulated as quasi-stationary fluid enthalpy generators, as function of the machine rotation speed and flow rate, with a direct or inverse relationship with the latter.

The characteristic function of enthalpy versus flow rate at different speeds is assigned in input files or point by point, following arbitrary profiles or estimated with similarity laws from a known function at nominal speed (fan law).

The characteristic map is extended even to working conditions beyond the surge and choking limits and for negative flow rates, in order to allow the continuation of the calculation even in cases of temporary misfunctioning of the control system. It is nevertheless approximated with a monotonic law in the surge zone too, to avoid numerical ambiguities, not being however of interest an accurate simulation in such unwanted conditions (Fig. 5).

The surge and choking limit curves are defined with analytical or numerical laws, assigned themselves as an input.

The procedure to calculate the flow rate delivered by the compressor, as a function of the total enthalpy head to be balanced and of the rotation speed, is illustrated in Fig. 6, while Fig. 7 shows the calculation scheme for the relevant discharge gas temperature.

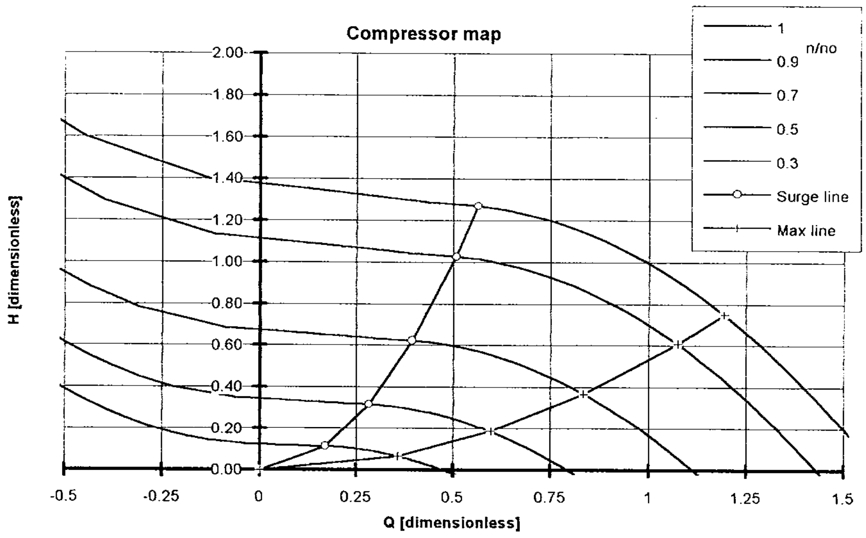


Fig. 5 - Complete characteristic curve of the compressor, obtained with a similarity law (outside the working limits the profiles are extrapolated)

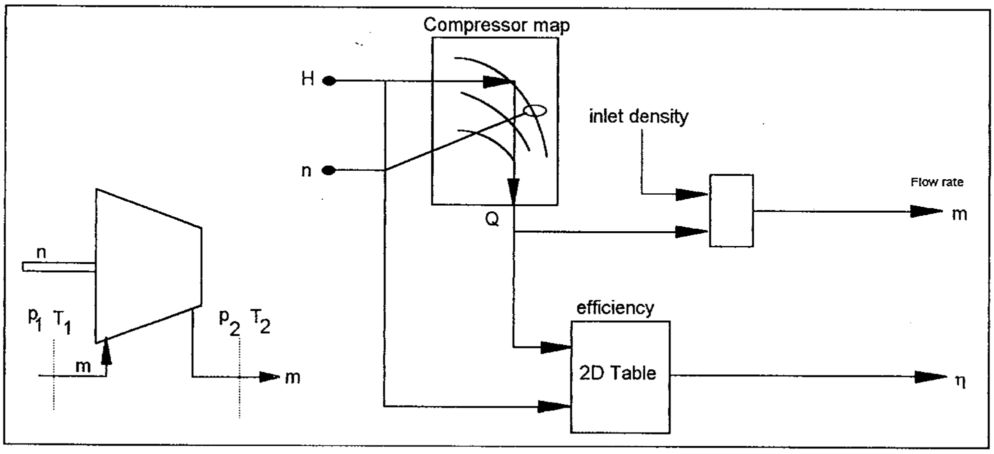


Fig. 6 - Calculation scheme of the flow rate delivered by the compressor

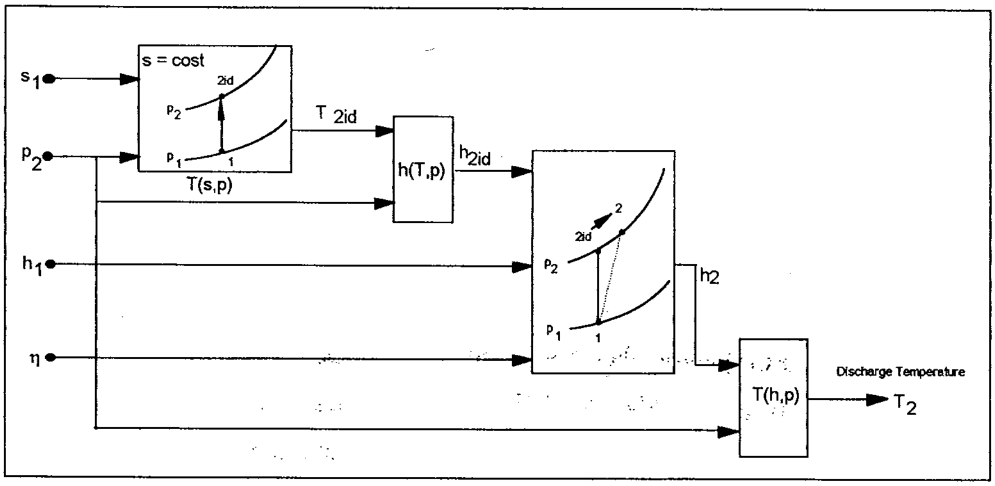


Fig. 7 - Calculation scheme of the discharge temperature

2.4. The Drivers

The driving engine (turbine or electric motor) is simulated, together with its controller, as an overdamped 2nd order dynamic block, i.e. responding to a variation of the input velocity with a linear dynamic characteristic of the 2nd order with real poles and time constants defined in input. Such approximation is acceptable, being of interest the behaviour of the gas in the plant rather than the internal state variables of the driver itself.

The working range and the above mentioned dynamic response are however bounded by a function defining the maximum available power (P_{max}) as function of the rotation speed (n).

Therefore, the driver speed response (n) is saturated with a law depending on the instantaneous power (P), i.e. depending on the distance between the working point (P,n), imposed to the driver by the compressor, and the maximum power curve (P_{max},n).

2.5. The K.O. Drums and the Air Coolers

The K.O. drums are simulated as adiabatic lumped capacities, connected to the pipeline and dynamically in equilibrium with the other subsystems.

The heat exchangers, usually of gas/air type (with pressured gas inside tubes), are simulated as a tube equivalent to the tube nest, with the gas side heat transfer coefficient calculated instantaneously as a function of the mean pressure and temperature and with the air side one calculated as a function of the fan velocity (in % of the maximum) and of the external air temperature, constant during the simulation but arbitrarily defined in an input file.

2.6. The Control System

As already mentioned, there are many control functions in a gas compression system, co-ordinated by a Performance Controller. ***COMPSYS*** can implement every scheme used in industry practice, which however could not be exhaustively described in this paper.

A basic description of the logic blocks is graphically summarised for the antisurge controller (Fig. 8), for the driver rotation speed (Fig. 9) and for the load sharing between parallel units (two in the example of Fig. 10). The latter pursues the following objectives:

1. To determine if the demanded flow rate can be delivered by only one compression train or by two (in the example) units.
2. To assure that none of the compression units run outside its working range.
3. To assure that, if not all the units can run at the same working point (equally distributed flow rate), one of them can work at a good efficiency point and the other at a complementary condition. If this results in the surge zone, the anti-surge control system, with hot and cold recycle, would obviously intervene, until all the units can be driven to an equally distributed load.

To each analog actuator a linear P.I.D. controller is connected, with the input signal determined by the above mentioned logical blocks. The P.I.D. transfer function is in the classical form Single Input-Single Output (SISO), with the parameters (Controller Gain, Reset Time and Derivative Time) defined in input for each controller.

The numeric model implements analog controllers equivalent to the digital ones actually used, because their sampling rate (ca. 25 Hz) is much greater than the characteristic response bandwidth of the system and so simulations run faster.

COMPSYS can also implement the Performance Controller, a higher level control system which simultaneously verifies different system variables, and their compatibility with the relevant objectives or acceptable ranges (antisurge, load sharing, pressure override control), determining at each time which of them must be considered as the primary variable to control and foreseeing any possible secondary variable which is getting near its assigned limit condition or curve. This action actually limits the intervention of the single controllers, improving the global efficiency of the system.

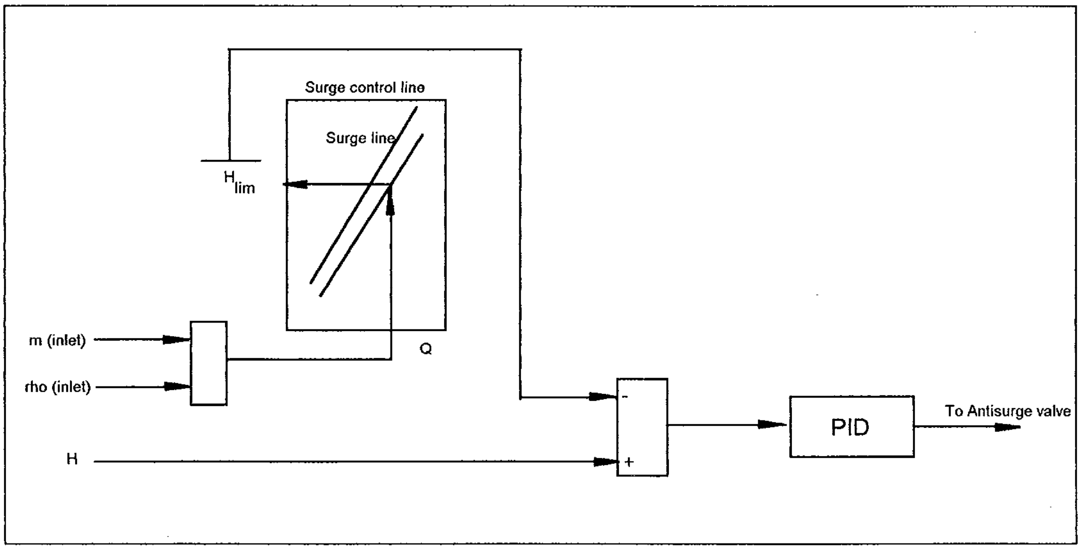


Fig. 8 - Control logic of the anti-surge valve (hot recycle)

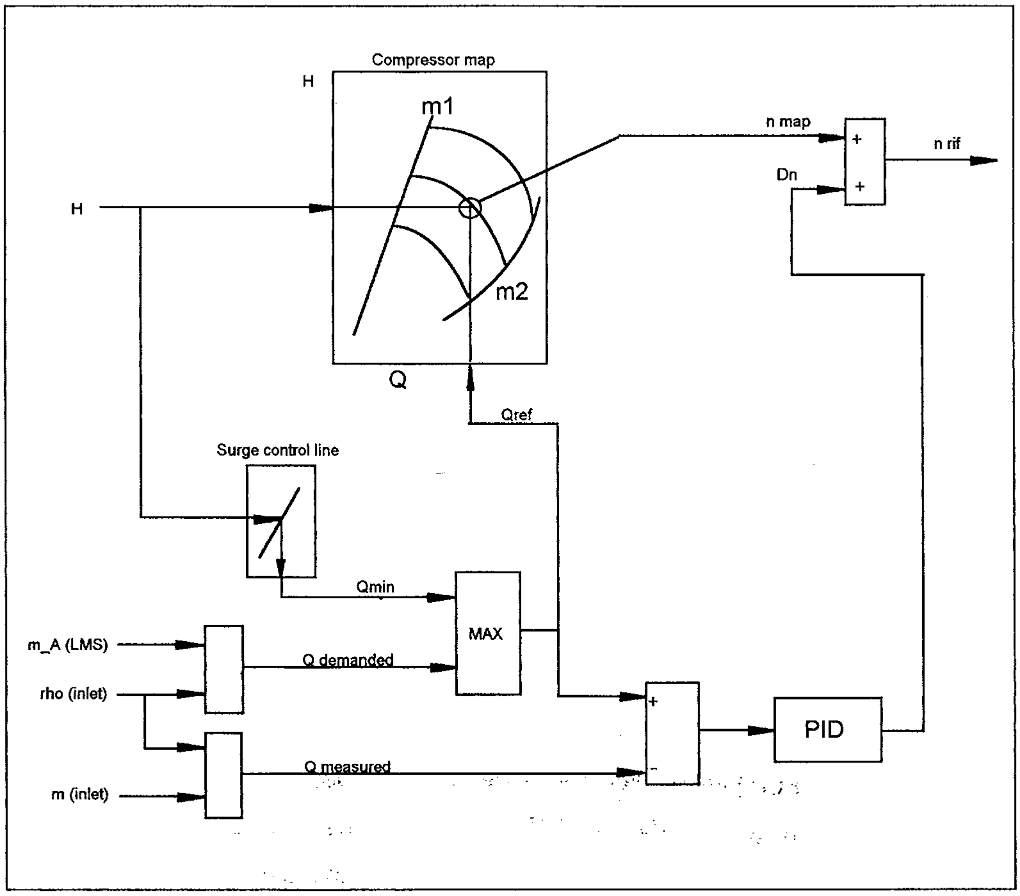
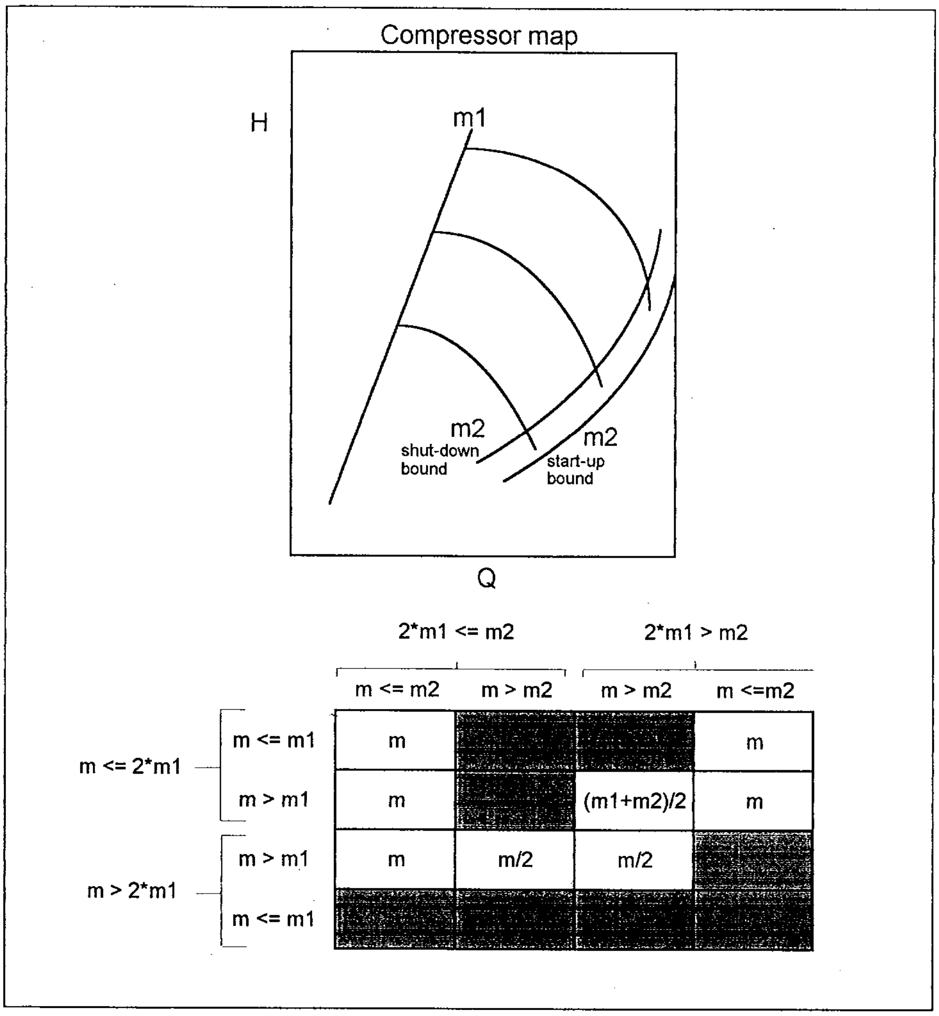


Fig. 9 - Control logic of the driver-compressor rotation speed



		2*m1 <= m2		2*m1 > m2	
		m <= m2	m > m2	m > m2	m <=m2
m <= 2*m1	m <= m1	m	▨	▨	m
	m > m1	m	▨	(m1+m2)/2	m
m > 2*m1	m > m1	m	m/2	m/2	▨
	m <= m1	▨	▨	▨	▨

Calculation of the flow rate demanded to one of the compressors (A):

m	Global flow rate demand to the plant
m1	Value of the flow rate on the limit line of the antisurge control
m2	Maximum value of the flow rate (near the choking line)

For the other compressor (B):

$$m_B = m - m_A$$

Fig. 10 - Karnaugh Map for the setting of the reference input of two parallel compression units (Load sharing Logic)

3. THE SIMULINK MODEL OF ***COMPSYS***

COMPSYS runs with a library of plant ***configurations***[3] based on the customer's requirements, assuring the maximum flexibility of use and the possibility of a later further extension of the configuration family to be studied.

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[3] The term ***configuration*** means the connected set of pipelines, piping accessories, containers, heat exchangers, compressors and relevant control systems, i.e. the set of ***components*** forming the ***system***, and corresponding to a definite process scheme, regardless of the dimensional data and characteristics of the ***components*** and of the fluid contained.
System means a configuration defined in all its dimensional and gas parameters.

Each configuration is associated to one SIMULINK model, containing different combinations of the components blocks corresponding to the physical blocks (compressors, pipes, exchangers, etc.).

Figs. 11 and 12 show a relatively simple configuration, with two parallel compressors (without heat exchangers[4]), and its SIMULINK scheme respectively.

On the left side of the diagram in Fig. 12 the physical inputs of the system are shown. Putting in evidence these inputs allows the definition of the relevant transfer functions, after a checking linearisation, and their immediate displaying. For the transients simulations, in the "IN" block some signal sources, definable at will, are gathered, with suitable logic schemes.

In the blocks of the top level scheme of Fig. 12, up to five levels of functional sub-blocks are nested. For instance, a single compressor (Fig. 13) is a second level block, which calculates the delivered flow rate, the outlet temperature, the power absorbed by the machine and the "stream vector" of the control variables, as functions of the inlet and outlet pressures, of the inlet temperature, the rotation speed and the valves positions, all in their turn depending on other blocks.

An example of low level block, relevant to a single valve, is shown in Fig. 14. It calculates the flow rate as a function of the up and down-stream pressures and temperatures and of the actuator position.

The interesting outputs of each block are addressed to the MATLAB Workspace for further elaboration and plotting. Also, to allow an "on line" monitoring of the simulations, "Scope" blocks are placed in the model, corresponding to some most interesting outputs.

As an index of the complexity of the models managed by ***COMPSYS***, it can be mentioned that the model shown in Fig. 12 has 43 state variables.

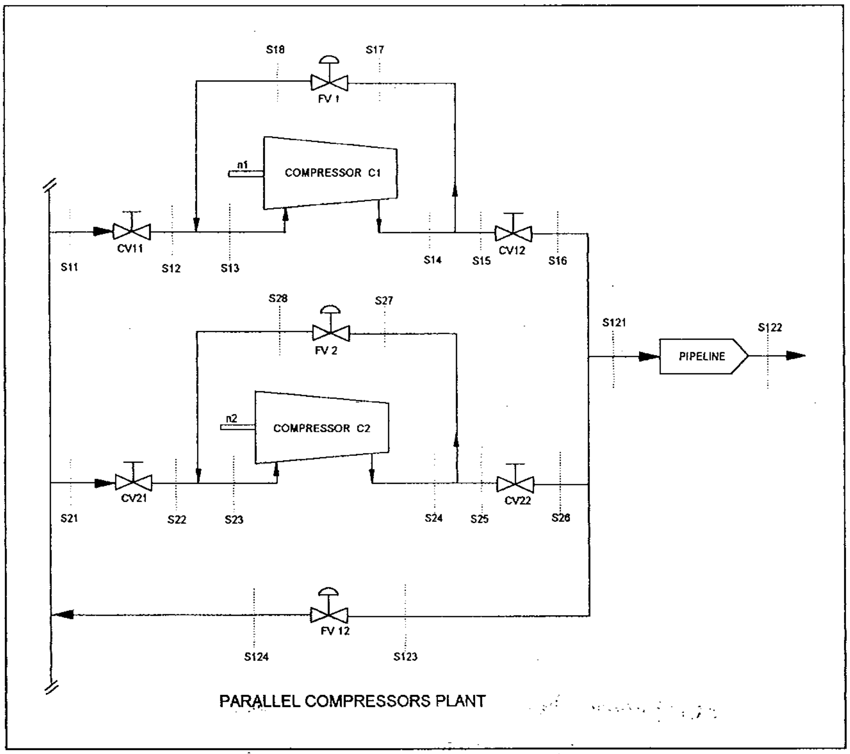

Fig. 11 - Scheme of a simple configuration of ***COMPSYS*** library

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[4] Drivers are not represented for simplicity.

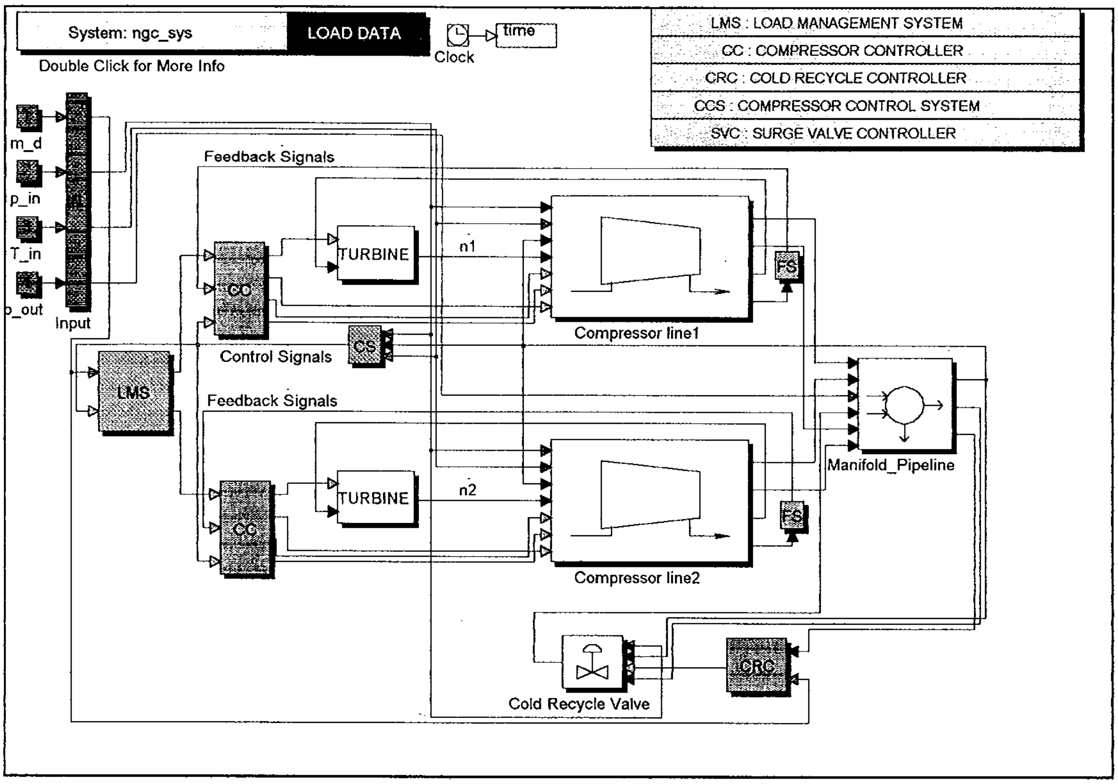

Fig. 12 - SIMULINK model (top level) of the configuration shown in Fig. 11

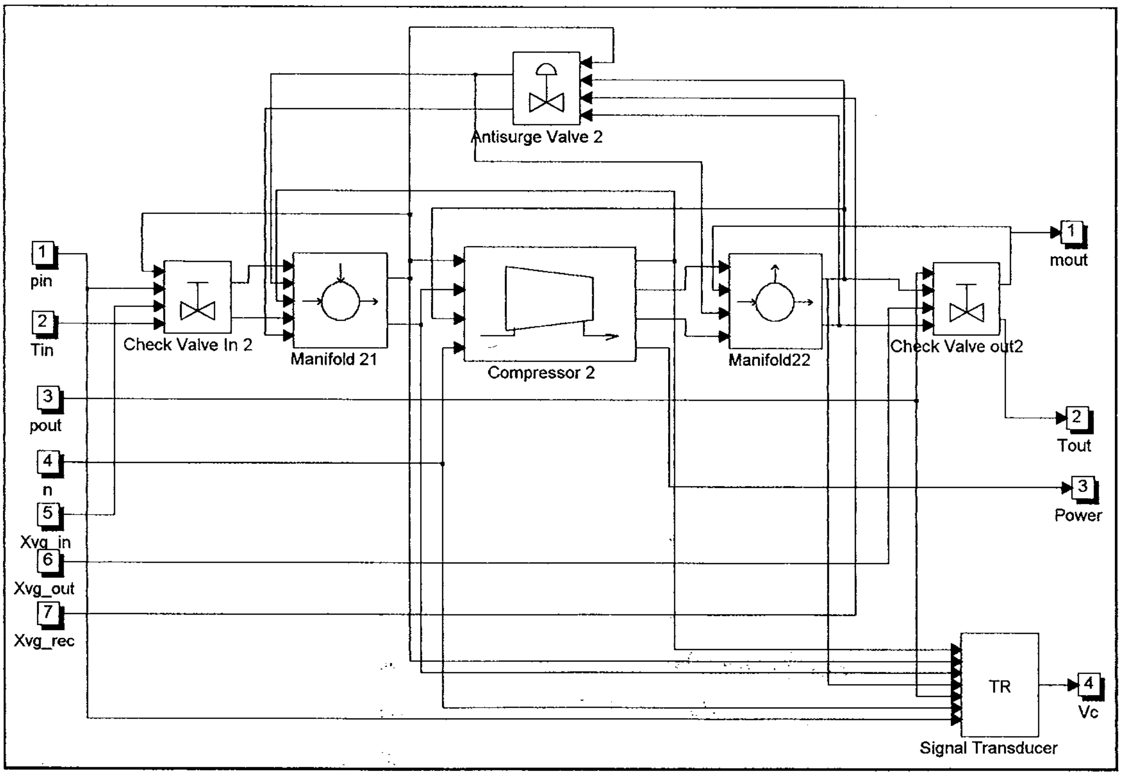

Fig. 13 - Second level block of the model in Fig. 12 - Compressor

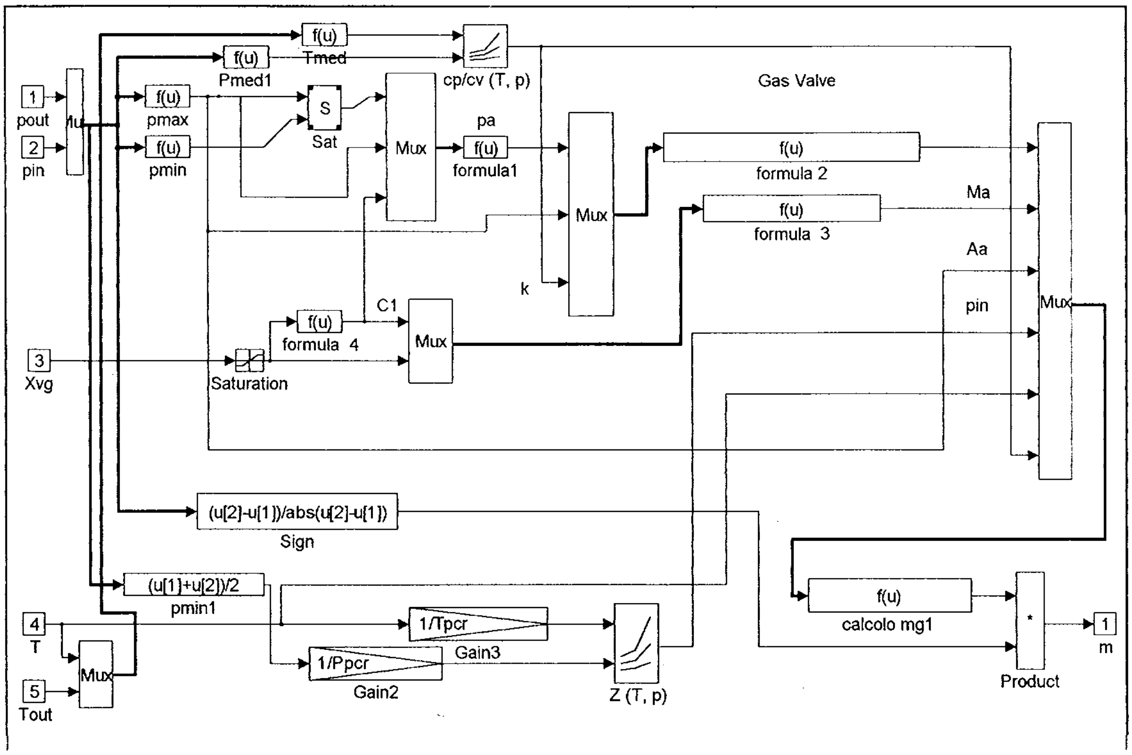

Fig. 14 - Example of low level block - Valve

4. USING ***COMPSYS***

COMPSYS is at present developed for consulting activity by the author. Its engineering is not yet at a product level, although the program is managed with the aid of graphic command windows. It is not provided, in fact, with a suitable robustness and flexibility for its graphical user interface (GUI), unlike another software product (ACUSYS [1]) already developed and published by the author. Instead, each algorithm, i.e. each functional block necessary for the implementation of various configurations, has been widely tested. As an example of the numeric robustness of the developed models, they can accept an inversion of flow in the conducts, that is not easily achieved with reliability, in order to simulate even anomalous or limit working conditions, without stopping the program or losing the validity of the calculated results.

Once developed as a product, ***COMPSYS*** would be provided with the following sets of files:

- configurations library,
- typical input files, relevant to each configuration,
- files to generate plots and/or output files,
- files for analyses management,
- calculation files.

The program operations will be managed by means of graphical interfaces such as that shown in Fig. 15, in order to avoid as much as possible the user to operate directly with MATLAB and/or SIMULINK and exploiting at best the features offered by MATLAB GUI's.

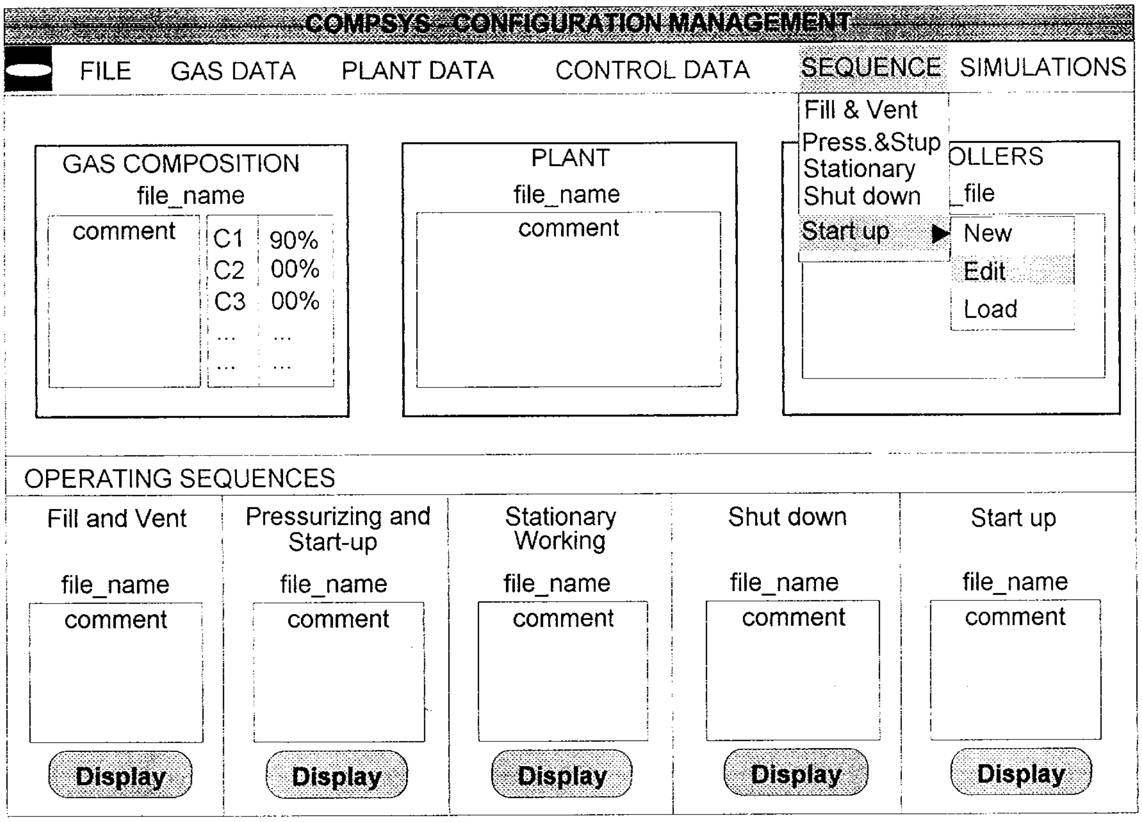

Fig. 15 - ***COMPSYS*** - Configuration Management window

Running ***COMPSYS*** requires an IBM compatible PC, preferably with 486 or Pentium® processor and, at least, a 50 MHz clock with 24 Mb RAM.

The necessary basic software is MATLAB (v. 4.2b or later) and SIMULINK (v. 1.3a or later), preferably with Accelerator, for MS-Windows® environment (v. 3.1 or later).

COMPSYS can use all the solving algorithms available in MATLAB-SIMULINK, but the most recommended is the 5th order Runge-Kutta method (RK45), because of the high non-linearity of the systems studied, with discontinuities in the input signals and in the components characteristics.

5. TYPICAL RESULTS

Figs. 16 and 17 show two examples of plots drawn by ***COMPSYS***, after the simulation of a transient lowering of flow rate demand for the system illustrated in Fig. 11. Fig. 16 represents, in the upper plot, the overlaid time histories of the global flow rate, of the one in the cold recycle loop and of the demanded one (input signal), and, in the lower plot, the flow rates of the two compressors, one of which is shut down because unnecessary (see under 2.6 and Fig. 10). Fig. 17 shows the trajectories of the working points for the two compressors on the respective characteristic maps, during the first 100 seconds of simulation. It can be noticed from this example that the antisurge control system is not fast enough to intervene and acceptable working limits are momentarily exceeded[5].

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[5] On the trajectories of Fig. 17 isochronous points are drawn, to allow an evaluation of the working point rate of variation.

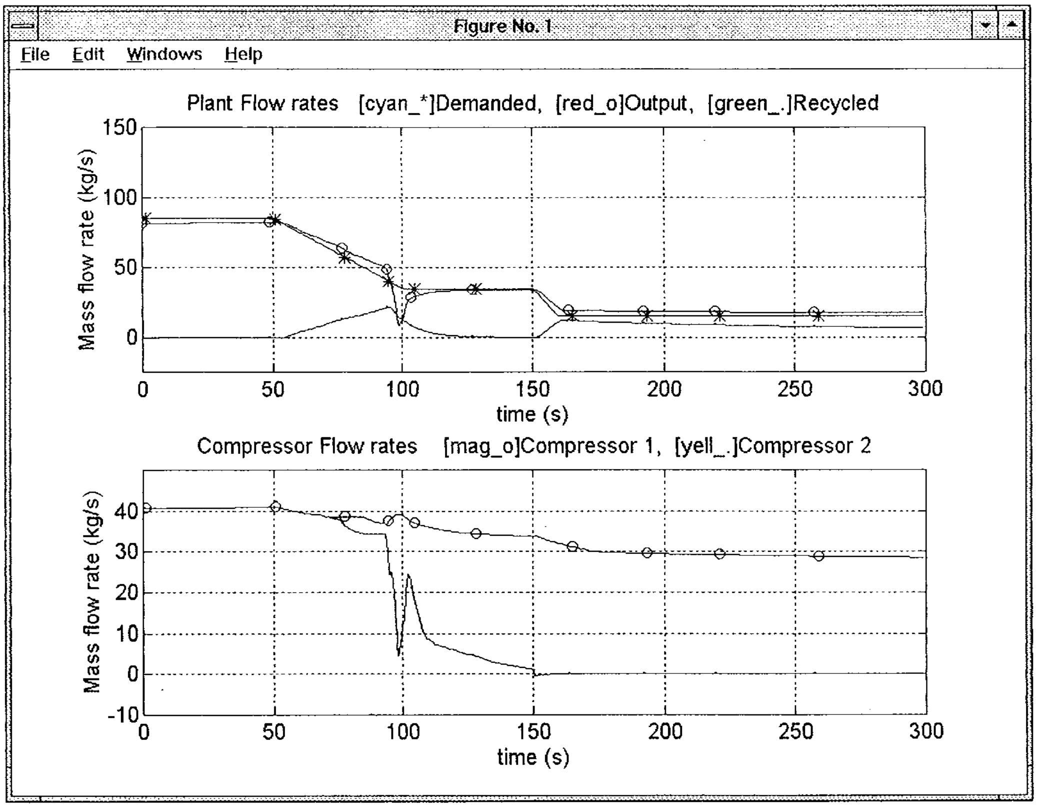

Fig. 16 - Varying input signal and system transient output.

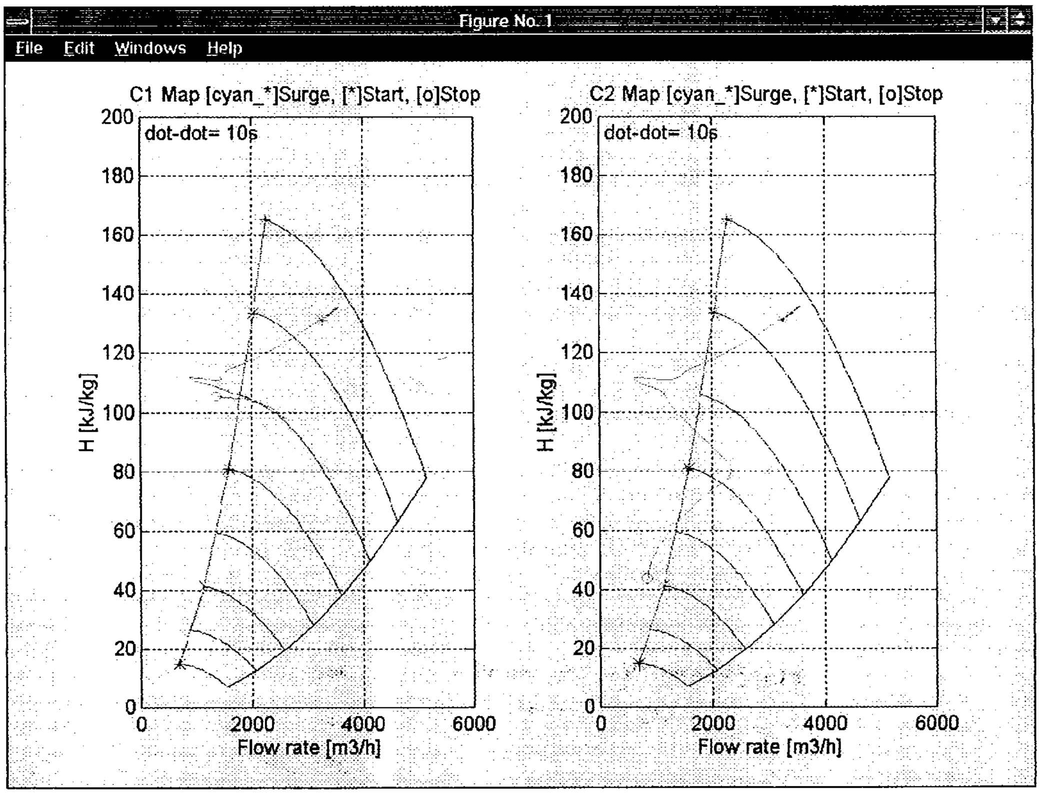

Fig. 17 - Trajectories of the working points on the characteristic maps of the two compressors.

6. THANKS

The author wants to thank Ing. Paolo Osti, who collaborated in the implementation of the basic models of ***COMPSYS***, and TEORESI S.r.l. for the technical support on MATLAB-SIMULINK.

7. REFERENCES

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