# SIMULATION OF A HVAC SYSTEM WITH THE HELP OF AN ENGINEERING EQUATION SOLVER

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## ABSTRACT

With the help of a so called “engineering equation solver” it is possible today to write directly executable equations. This means that the modeling can be made fully transparent and easy to adapt to the specific needs of any user.

First principle models are very easy to produce, with reference to classical engineering processes.

A same set of equations can even be used for different tasks as system sizing, parameter identification and simulation.

An example of system modeling is presented in the paper; it concerns a whole chilling plant, with screw chillers, cooling towers, equilibrium bottle, ice storage system, heat exchangers and pumps.

First principle models are separately demonstrated for all these components. Components models are then assembled together in order to represent the whole chilling plant. Simulation results obtained with this assembly are used in order to generate a set of polynomial equations, easy to connect to the building, through its “secondary” HVAC subsystems (air handling and terminal units).

## SIMULATION USE

Too much exclusive attention has been paid until now to only one particular stage of the Building life cycle (BLC): the detailed design. The first and the last stages have been almost forgotten: the early design, when the most important decisions are to be made, the commissioning, when the most important verifications should be done, and the system operation, with minimisation of global costs, including maintenance (Lebrun J. et al, 1999).

These three very different stages of BLC have something in common: they require a very good understanding of the global system behaviour. The bottleneck of such an approach is not the computer, but the human brain. Even if a lot of details must be taken into consideration in order to get a realistic simulation, it's very helpful to "simplify" the simulation models in such a way to reduce the number of variables and parameters to be manipulated.The main benefits of such a simplification are a better feeling of the user about sensitivities of the model and also a lower risk of mistake in input preparation and in output interpretation.

Before the first energy crisis of the seventies, simulation tools have been mostly developed in view of equipment sizing. This was the very first concern: which size to give to all components in order to satisfy the requirements at minimal investment costs.

From the end of the seventies until the beginning of the eighties, all attention was re-oriented towards long term energy consumption. Sizing problems were often forgotten by tools developers and different tools had to be used (with different parameters and input variables !) in the detailed design process.

It is clearer now that both energy and power impacts have to be taken in consideration at all stages of BLC.

With the deregulation of electricity market and the outcome of "dynamic" pricing, it's obvious that efficient dynamics simulations (in real and fictitious times) are also very welcome …

## MODEL CARACTERISATION

Models can be categorised into "white", "grey" and "black" boxes according to their physical meaning. At very first look, the choice among these three categories should result from a compromise between accuracy and simplicity. But a "white" box model is neither necessarily more accurate, nor more difficult to manipulate than a "black" box…

A good engineering approach consists in exploring the problem by starting from "the end", i.e. from the simulation outputs and going back to the corresponding inputs and parameters which the user might need to "manipulate".

Different (white, grey and black box) models can be built in order to interconnect among themselves the outputs, inputs and parameters. And thanks to the use of an “Engineering Equation Solver” (Klein, 2001), most mathematical obstacles are being removed, making the model choice much less dramatic : transparency (whiteness) and realism have no more to be sacrificed to equation solving easiness.

But simplicity is welcome, in quality (equations is easy to understand ) and in quantity (limited number of equations and of corresponding variables).

A good way to ensure the model understandability is to start from fully physical approach (full whiteness), but also from simplest assumptions. These two options are compatible, if the real component considered is replaced by a set of elementary (well-known) processes, according to a “let’s do as if” modeling scenario (Bourdouxhe J.P. et al, 1999).

The numbers of elementary processes considered can be increased progressively until the model accuracy is considered as sufficient. At a later stage only, and for pure mathematical convenience (algorithm robustness), a black box can be generated: for example a set of polynomial equations whose coefficients are fitted on the results given by the "reference" model.

## MODEL STRUCTURE

Most engineering models are developed in such a way to answer two questions :

1) What is the "useful" output of the component?

2) How much does it "cost"?

If a feedback control is associated to the component, its "useful" output can be defined as the degree of achievement of some requirement (for example a temperature set point).

Without feedback control (i.e. if the component is simulated in "full load" regime), the useful output corresponds to the component "capacity", i.e. the highest requirement achievable.

"Costs" can be expressed in various terms, such as energy, power, flow rate, etc.

In order to be able to answer both questions (“how much” and “at which cost”), the model has to be supplied with three different groups of inputs :

1) The “parameters”, which are describing the component considered and currently not allowed to vary during a simulation (fluid nature, building and equipment characteristics, etc).

2) The requirement(s);

3) The constrain(s), which do affect the component performances (fluid supply and surrounding temperatures, etc.). These constrains might have to be defined as secondary outputs of other components included in the system.

The definition of input and output variables is always a bit arbitrary: it corresponds to one preferred way to “handle” the model, but not necessarily to what are the physical "causalities" inside the system considered. Even a so-called "causality" is nothing more than a model making easier the understanding of the phenomena: these ones are described as if some variables were acting on some other ones.

Modern equation solvers don't need to be provided with specific causalities; they are exploring the mathematical system in such a way to identify all possible sequences and also all blocks of equations that have to be solved simultaneously.

But a selection of "typical" causalities remains very useful when having to run a model alone, in order to test it, or in order to identify its parameters.

## EXAMPLE : MODELLING OF A COOLING PLANT

The cooling plant considered here is a real one: it is installed in the so-called "Justus Lipsius" Building used by the of European Ministery Council in Brussels [George, B. et al, 1999]. It includes a set of four twin-screw chillers, four ice-storage tanks and five cooling towers. Chillers and ice storage system are interconnected through a glycol water circuit including and equilibrium bottle. The interconnection between the cooling plant glycol water circuit and the building cold water distribution network is realised through a set of five flat-plate heat exchangers.

All components of a same set are mounted in parallel. A convenient simplification consist in replacing each set of components by an equivalent one : the system is represented “as if “ counting only one heat exchanger, one ice storage tank, one chiller and one cooling tower. Each set of pumps is also replaced here by only one. This simplification is not affecting the final accuracy, providing that each equivalent component is carefully described in part load regime: pumps, chillers and cooling towers can be used in “cascade”, which is not the same as using all these components together at a same part load regimes. In some circumstance, as for system management and diagnosis, it might be helpful to go back to a representation of all real components.

In the building considered, some cooling is always necessary. This can be achieved in four different running modes :

- by using the ice storage system only (and not the chillers);
- by using the chillers only (and not the ice storage);
- by using both the chillers and the ice storage in parallel;
- by using the chillers for both water cooling and for charging the ice storage system at same time.

The schema on Figure 1 can be used to represent the three first regimes, while the schema on Figure 2 corresponds to the fourth regime.

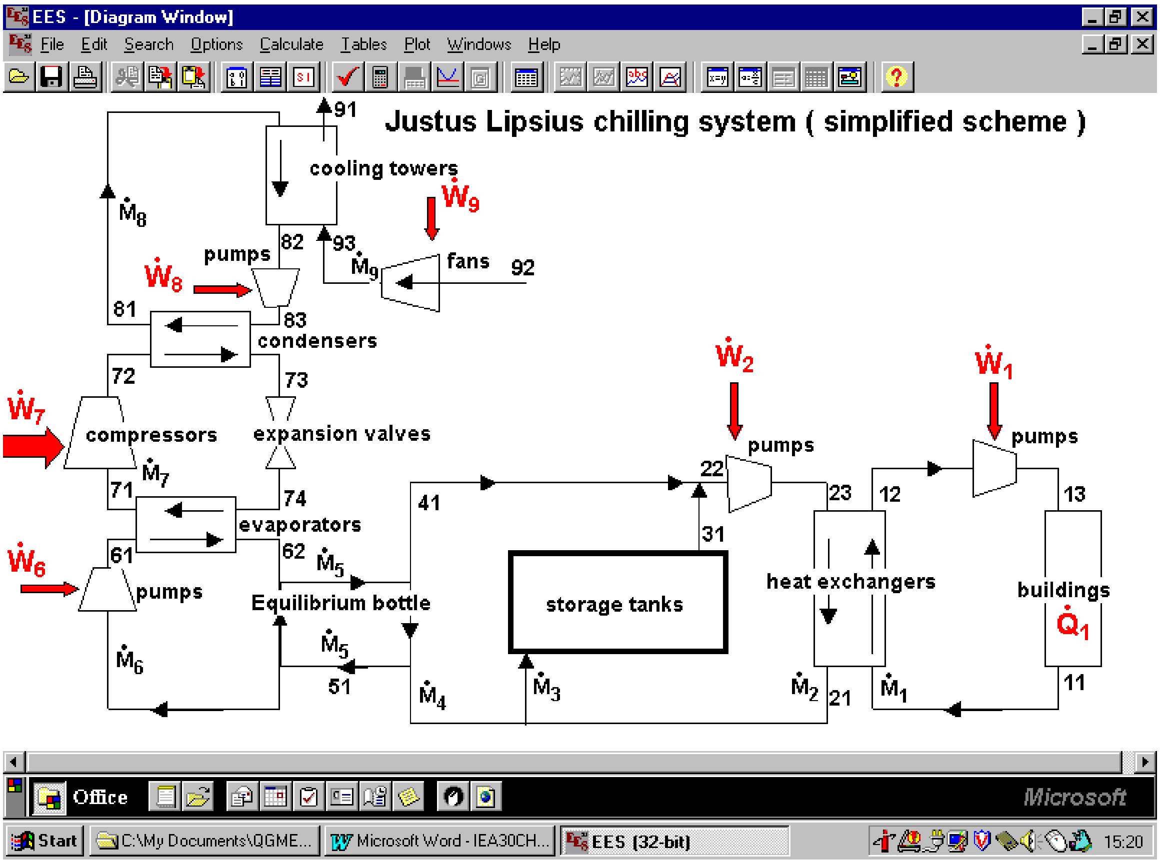


FIGURE 1 : 3 first running modes: use of the chillers and the ice storage system (separately or at same time).

A set of 9 different fluid loops are here distinguished. They are numbered from 1 to 9 in Figure 1, by going from the chilled water circuit (1) until the air circulation accross the cooling towers (9).

With the solver used here, it's possible to define the variables indicated in diagrams such as figures 1 and 2 as input and output variables. In such case, each diagram becomes a control panel in which the user may act on the inputs and observe the outputs, without having to care to the equations.

Two other options can be selected:

One consists in using one or several variables to generate tables (and corresponding plots) for parametric studies.

Another one consists in producing separate component simulation modules, which are easy to assemble when having to deal with large systems.

## COMPONENT MODELLING AND SIMULATION

Most of the component models used here are transposed from the ASHRAE primary toolkit (Bourdouxhe J.P. et al, 1999). The transposition is very easy and fully transparent with the solver available as shown here after.

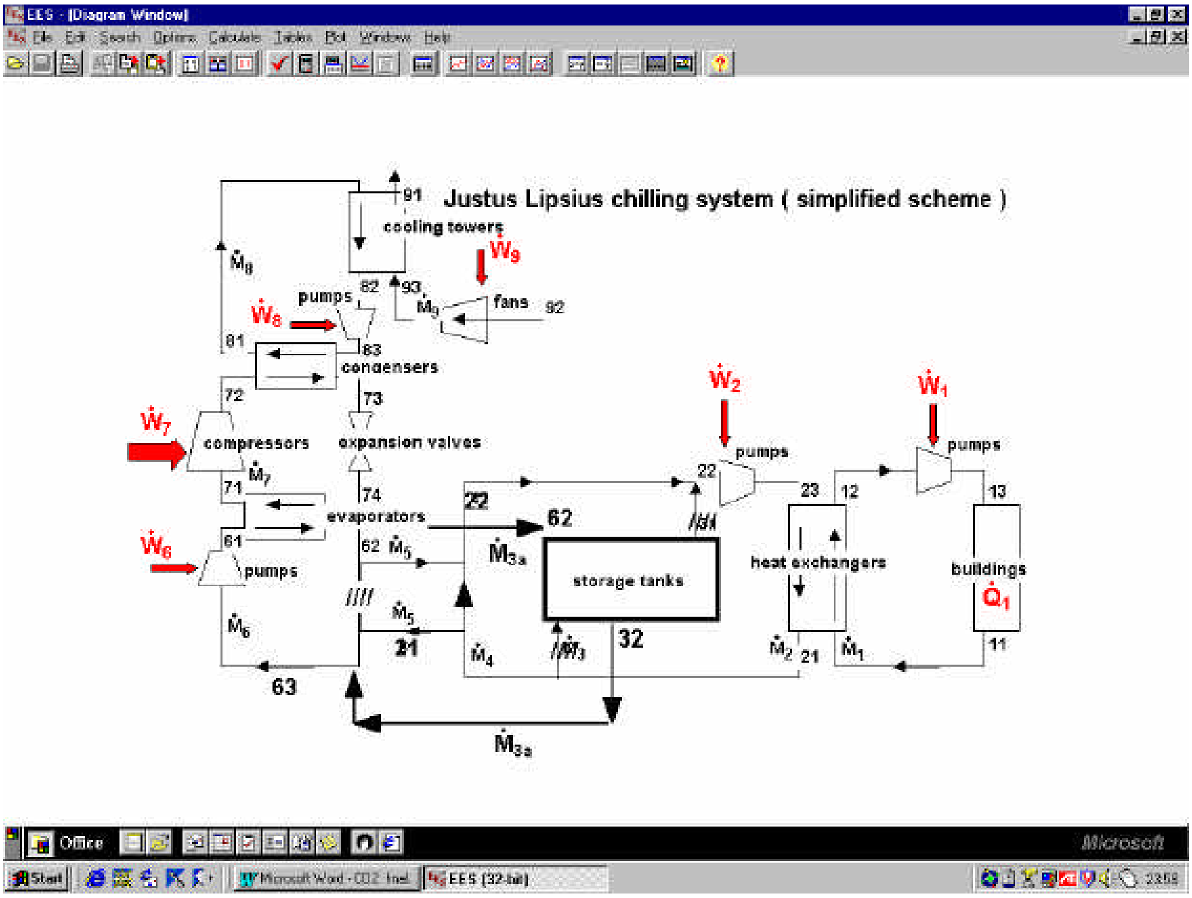


FIGURE 2 : fourth running mode: use of the chiller for water cooling and recharging the ice storage system at same time.

Glycol/Water heat exchangers (loops 1 and 2)

The set of five flate plates heat exchangers is modelled as only one classical counterflow heat echanger. The fluid-to-fluid thermal resistance (R1,2) can be decomposed into two convective resistances (R1 and R2) and one metallic resistance (Rm1,2) mounted in series.

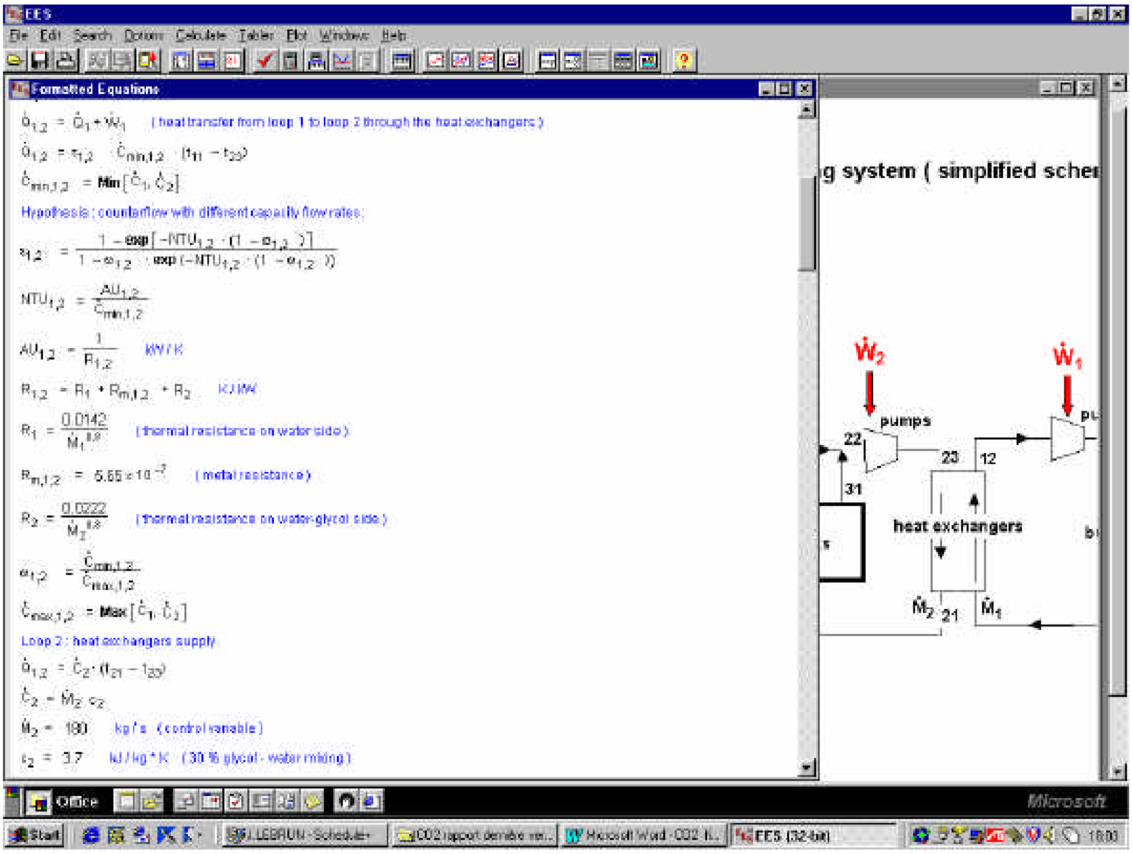
R1 and R2 are related to fluid flowrates $\dot{M}_1$ and $\dot{M}_2$ respectively. Formatted equations are given in the print screen of Figure 3.

Ice storage system (loop 3)

A convenient approach consists in replacing this complex system by a classical semi-isothermal heat exchanger (with isothermal side at 0 °C) whose heat transfer coefficient must be identified from simulation results got with a more realistic model and or from experiment.

In the case considered, the global heat transfer coefficient is always decreasing along the charging and discharging processes: this decrease is due to both an increase of thermal resistance and to a decrease of active heat exchange area (plug flow effect).

Examples of simulation results produced by the manufacturer with his own software were reprocessed in such a way to make appear a unique relationship between the global heat transfer coefficient and the energy content of the ice storage system.



$\dot{Q}_{1,2} = \dot{Q}_1 + \dot{W}_1$ ( heat transfer from loop 1 to loop 2 through the heat exchangers )

$\dot{Q}_{1,2} = \varepsilon_{1,2} \cdot \dot{C}_{min,1,2} \cdot (t_{11} - t_{23})$

$\dot{C}_{min,1,2} = \mathbf{Min}[\dot{C}_1, \dot{C}_2]$

Hypothesis : counterflow with different capacity flow rates :

$$\varepsilon_{1,2} = \frac{1 - \mathbf{exp}[-NTU_{1,2} \cdot (1 - \omega_{1,2})]}{1 - \omega_{1,2} \cdot \mathbf{exp}(-NTU_{1,2} \cdot (1 - \omega_{1,2}))}$$

$$NTU_{1,2} = \frac{AU_{1,2}}{\dot{C}_{min,1,2}}$$

$AU_{1,2} = \frac{1}{R_{1,2}}$ kW / K

$R_{1,2} = R_1 + R_{m,1,2} + R_2$ K / kW

$R_1 = \frac{0.0142}{\dot{M}_1^{0.8}}$ ( thermal resistance on water side )

$R_{m,1,2} = 5.65 \times 10^{-7}$ ( metal resistance )

$R_2 = \frac{0.0222}{\dot{M}_2^{0.8}}$ ( thermal resistance on water-glycol side )

$$\omega_{1,2} = \frac{\dot{C}_{min,1,2}}{\dot{C}_{max,1,2}}$$

$\dot{C}_{max,1,2} = \mathbf{Max}[\dot{C}_1, \dot{C}_2]$

Loop 2 : heat exchangers supply

$\dot{Q}_{1,2} = \dot{C}_2 \cdot (t_{21} - t_{23})$

$\dot{C}_2 = \dot{M}_2 \cdot c_2$

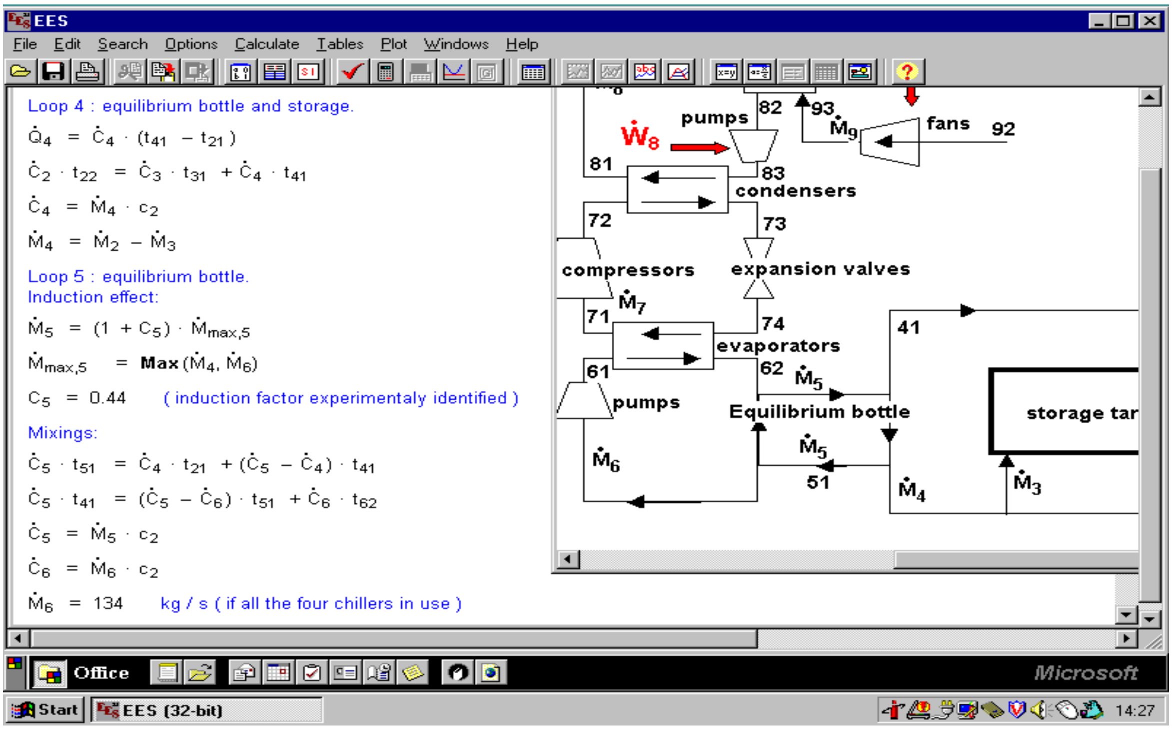
$\dot{M}_2 = 180$ kg / s ( control variable )

$c_2 = 3.7$ kJ / kg * K ( 30 % glycol - water mixing )

FIGURE 3 : modelling of the heat exchangers

Equilibrium bottle (loops 4, 5 and 6)

A simple model is proposed in Figure 4: internal mixing is supposed to be caused by induction.



Loop 4 : equilibrium bottle and storage.

$\dot{Q}_4 = \dot{C}_4 \cdot (t_{41} - t_{21})$

$\dot{C}_2 \cdot t_{22} = \dot{C}_3 \cdot t_{31} + \dot{C}_4 \cdot t_{41}$

$\dot{C}_4 = \dot{M}_4 \cdot c_2$

$\dot{M}_4 = \dot{M}_2 - \dot{M}_3$

Loop 5 : equilibrium bottle.
Induction effect:

$\dot{M}_5 = (1 + C_5) \cdot \dot{M}_{max,5}$

$\dot{M}_{max,5} = \mathbf{Max}(\dot{M}_4, \dot{M}_6)$

$C_5 = 0.44$ ( induction factor experimentally identified )

Mixings:

$\dot{C}_5 \cdot t_{51} = \dot{C}_4 \cdot t_{21} + (\dot{C}_5 - \dot{C}_4) \cdot t_{41}$

$\dot{C}_5 \cdot t_{41} = (\dot{C}_5 - \dot{C}_6) \cdot t_{51} + \dot{C}_6 \cdot t_{62}$

$\dot{C}_5 = \dot{M}_5 \cdot c_2$

$\dot{C}_6 = \dot{M}_6 \cdot c_2$

$\dot{M}_6 = 134$ kg / s ( if all the four chillers in use )

FIGURE 4: Modeling of the equilibrium bottle.

Screw chillers (loops 6, 7 and 8)

Examples of simulation results obtained with a reference model are plotted in Figure 5. Internal leakage and slide vane control are included in this model.

The curves of Figure 5 show how the cooling capacity ($\dot{Q}_{ev}$) may vary as function of the supply temperatures of both "secondary" fluids ($t_{sucs}$ at condenser supply and $t_{suev}$ at evaporator supply). The change of slope correspond, for each curve, to the effect of the slide vane control, which is protecting the compressor motor against overloading.

A simplified model of the chiller compressor is presented in Figure 6. It takes electromechanical losses and part load internal losses into account.

Evaporator and condenser (not included in Figure 6) are represented as semi-isothermal heat exchangers.

Cooling towers (loops 8 and 9)

They are represented as an equivalent (counter flow) heat exchanger supplied on one side by water and on the other side by a fictitious fluid replacing air.

A fictitious specific heat is defined as the ratio between air enthalpy and corresponding wet bulb temperature variations.

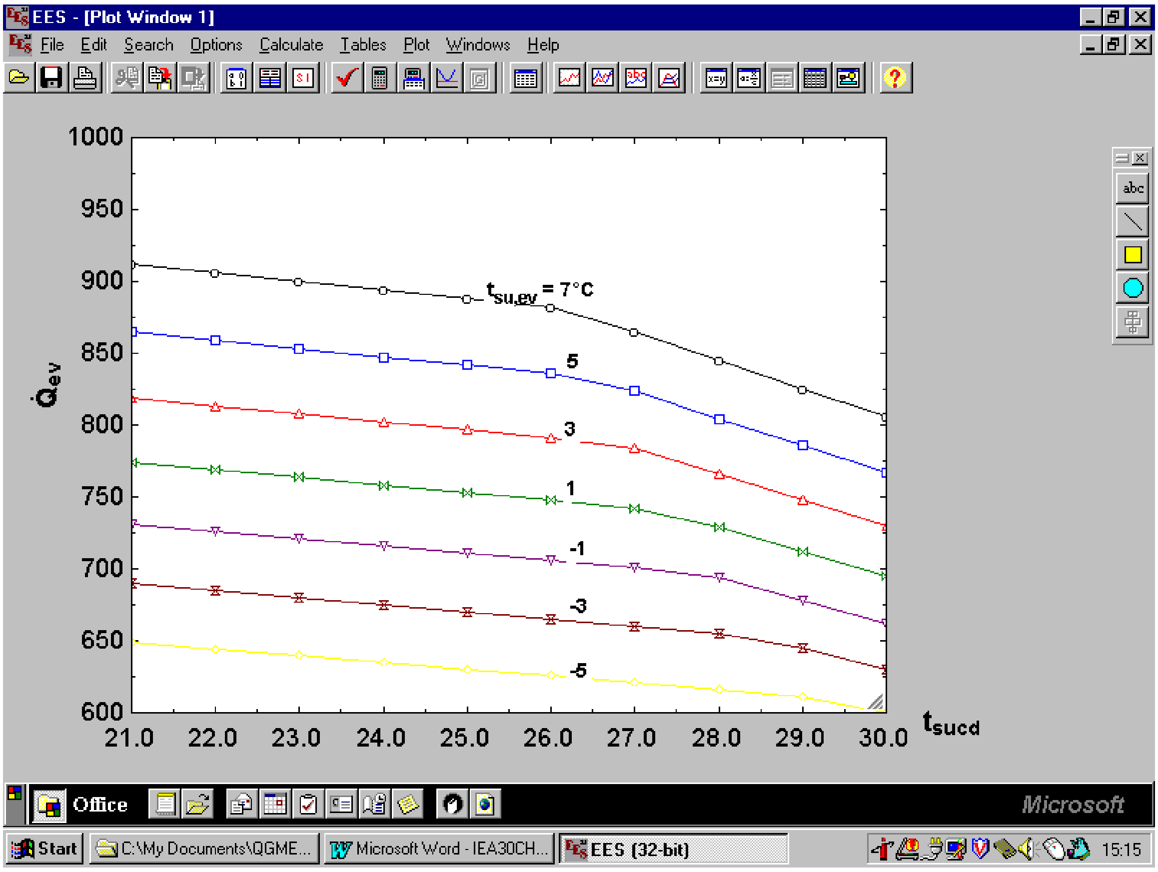
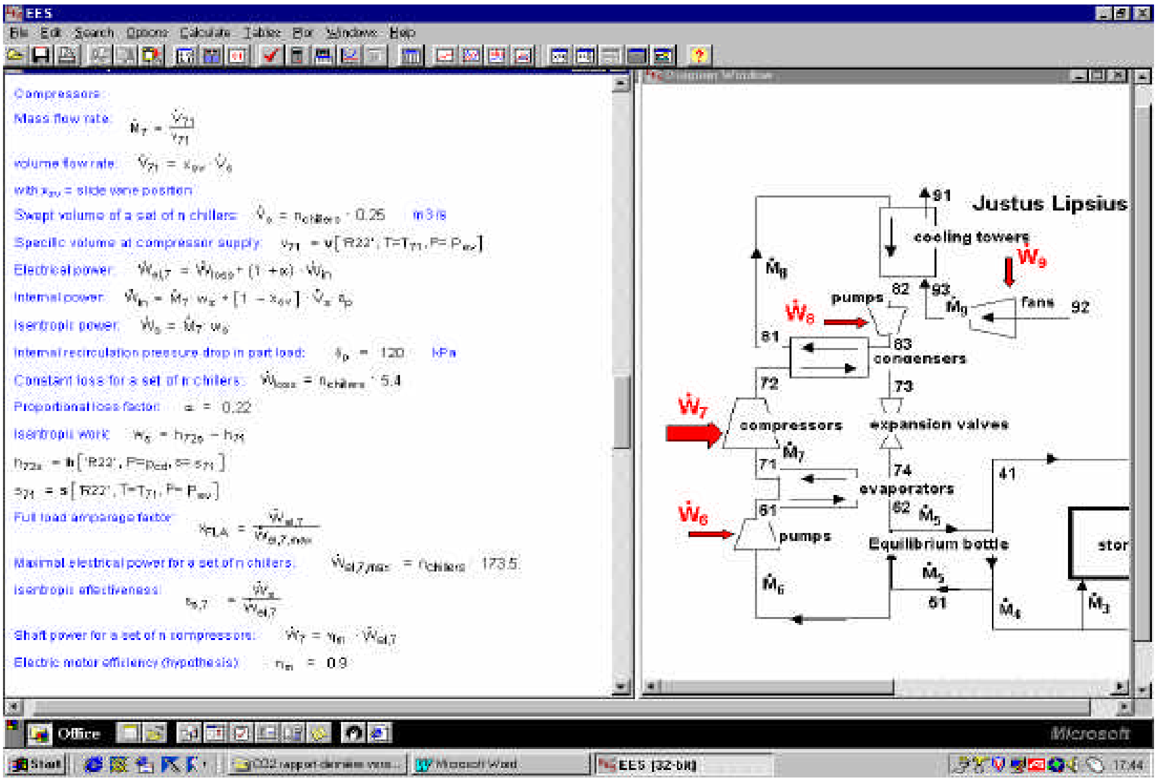


FIGURE 5 : simulation of a screw chiller with internal leakage and slide vane control



Compressors:

Mass flow rate: $\dot{M}_7 = \frac{\dot{V}_{71}}{v_{71}}$

volume flow rate: $\dot{V}_{71} = x_{sv} \cdot \dot{V}_s$

with $x_{sv}$ = slide vane position

Swept volume of a set of n chillers: $\dot{V}_s = n_{chillers} \cdot 0.25$ m3/s

Specific volume at compressor supply: $v_{71} = v['R22', T=T_{71}, P=P_{ev}]$

Electrical power: $\dot{W}_{el,7} = \dot{W}_{loss} + (1+\alpha) \cdot \dot{W}_{in}$

Internal power: $\dot{W}_{in} = \dot{M}_7 \cdot w_s + [1 - x_{sv}] \cdot \dot{V}_s \cdot \delta_p$

Isentropic power: $\dot{W}_s = \dot{M}_7 \cdot w_s$

Internal recirculation pressure drop in part load: $\delta_p = 120$ kPa

Constant loss for a set of n chillers: $\dot{W}_{loss} = n_{chillers} \cdot 5.4$

Proportional loss factor: $\alpha = 0.22$

Isentropic work: $w_s = h_{72s} - h_{71}$

$h_{72s} = h['R22', P=p_{cd}, s=s_{71}]$

$s_{71} = s['R22', T=T_{71}, P=P_{ev}]$

Full load amperage factor: $x_{FLA} = \frac{\dot{W}_{el,7}}{\dot{W}_{el,7,max}}$

Maximal electrical power for a set of n chillers: $\dot{W}_{el,7,max} = n_{chillers} \cdot 173.5$

Isentropic effectiveness: $\varepsilon_{s,7} = \frac{\dot{W}_s}{\dot{W}_{el,7}}$

Shaft power for a set of n compressors: $\dot{W}_7 = \eta_m \cdot \dot{W}_{el,7}$

Electric motor efficiency (hypothesis): $\eta_m = 0.9$

FIGURE 6 : chillers simplified modelling

## MODELLING OF THE WHOLE COOLING PLANT

A correct modeling of the plant has to associate all previous components together and also to include all "auxiliary" components which do consume energy (pumps and fans).

Different configurations (as for example Figures 1 and 2) may have to be considered for different running modes. Examples of simulation results got in the second running mode (chillers only) are presented in Figure 7.

Such results can be used to generate simple polynomial laws, relating for example, the electrical consumption of the cooling plant ( $\dot{W}_{elp}$ ) to the useful chilling power ( $\dot{Q}_1$ ) and to the outside wet-bulb temperature ($t_{out,wb}$).

Different strategies can be experimented with the reference model, by varying for example the numbers of chillers, of cooling tower and of pumps involved.

Every strategy may conducts to a specific set of curves such as presented in Figure 10 and to specific polynomial law.

## CONCLUSIONS

The use of an "Engineering Equation Solver" makes much easier model development as well as system simulation. A same set of equations can be used for sizing and simulating a whole system.

This process is fully transparent : equations can be displayed as in a text look, but they are written as directly executable. Simplified models (set of polynomial equations) can be generated at any time on the basis of simulation results obtained with a reference model. This makes easier the interconnections among various subsystems as, for example, the "primary" and "secondary" HVAC subsystems and the building.

New model libraries can easily be built on this basis.

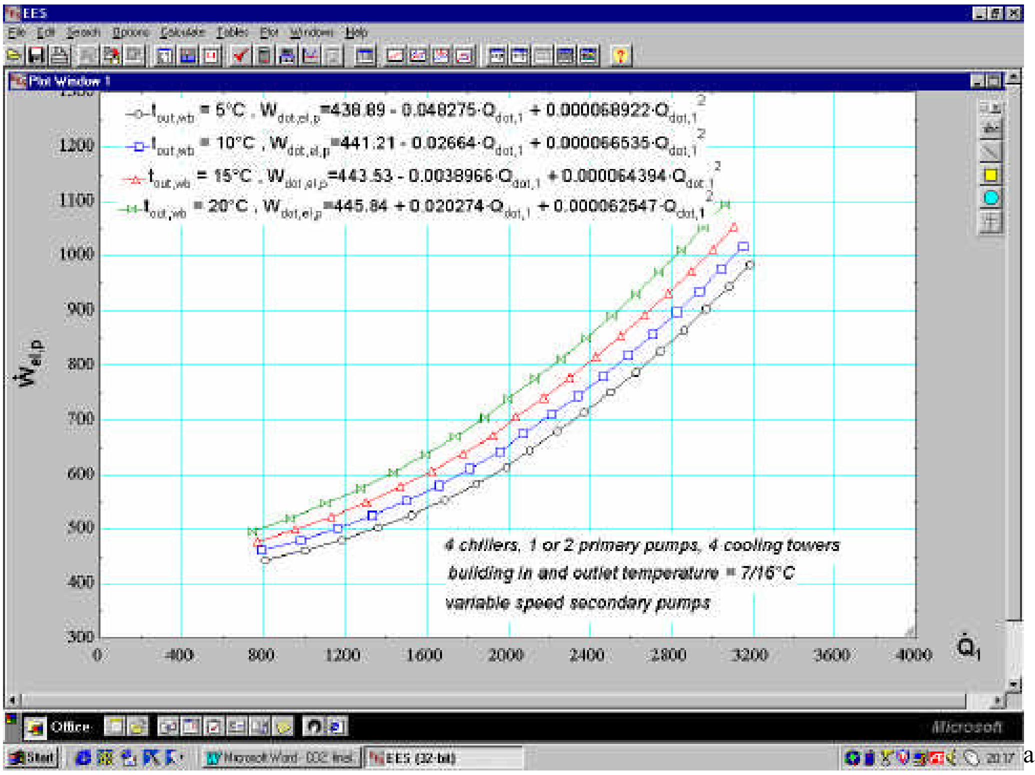


FIGURE 10 : electrical consumption as function of the useful chilling power, without using the ice storage system

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