HVAC Elements Modeling and Implementation for Net-zero Energy Building Applications

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***Abstract*—It is well known that rising energy prices have lead scientists to focus a special attention over resident or commercial building energy efficiency. Recent advances in digital technologies also encourage the development of a wide range of HVAC (Heating, Ventilation and Air Conditioning) automation systems for "net-zero energy building" strategies implementation. In topic with these emerging trends, this paper presents the modeling and software implementation research efforts of several HVAC elements, as basic components of a specially conceived "intelligent house" at Debrecen University. These components have been designed to overcome same of the actually existing deficiencies and emptiness in the HVAC systems modeling and simulation processes. Their original models have been implemented as novel VI (Virtual Instruments) by using the graphical oriented LabView software toolkit. Beside the elaborated mathematical models concrete software implementation examples are provided in the paper. These models are suited to become a useful software toolkit for implementing HVAC systems for net-zero energy building approaches, offering a feasible solution for future developments and research.**

I. Introduction

By the purest definition, a net-zero building (resident or commercial) produces all the energy it needs on site by using renewable energy sources and technologies. In other words, it draws no more power from the grid than it gives back by generating energy from non-polluting locally available resources [1, 2]. The net-zero energy is a general term applied to a building with a net energy consumption of zero over a typical year. In such a case the amount of energy provided by on-site renewable energy is equal or even greater to the amount of energy used by the building (obtained from traditional fossil fuels). However, rising energy process have led to a buzz over building efficiency and buildings that produce as much energy on-site as they consume are becoming more common. In some countries nearly 30-40% of the nation's energy is consumed by resident or commercial buildings. Making them more energy-efficient it means that would not only save expenses but also drastically reduce carbon emissions. Therefore, projects and research efforts that are involved in development of net-zero energy buildings are highly welcome and express a continuously emerging trend of this research area becoming an important task of the engineering community.

Obviously, buildings that uses non-polluting sources they generates energy onside, embedding complex HVAC systems, supervising and event monitor systems, or other complex automation systems that operates together to achieve the above mentioned net-zero energy goal are named in international references as "intelligent buildings" [2, 3]. The intelligent buildings embeds the climate control, the lighting technologies, the energy supply and its control systems, the building security and supervising systems, the doors and windows state monitoring system, the use of renewable energy sources, the internal- and external sensors, the data acquisition and data processing systems, the computer networks, the remote control systems, the digital control systems, etc. All the above ranked complex systems are linked in same way to the zero or nearly-zero energy building concept main problem. However, a common behaviour of the intelligent building's all sub-systems that they are designed and operated with the main scope to ensure that the yearly energy consumption amount by using traditional fossil fuels must be the same or even lower than the locally produced renewable energy amount. One of the most important advantages of the locally produced energy (beside its non-polluting character) is that it is totally free from the expensive transmission and distribution charges. Moreover, its production rate can be conveniently adapted to the local consumer needs and it's possible also to solve the energy storage issues.

By using integrated design and building technologies, designers are able to determine which energy efficiency strategies and what type of renewable on-site generation will contribute to higher energy performance to meets the requirements of the building considered.

Considering the importance of the topic, the advancement in this scientific area it is highly improved by academic research as well. There the engineers involved generally agree that in order to cover all the theoretical and technological challenges hided under the "intelligent building" concept a well stated development strategy it is required. As a major task of this endeavor, the adequate HVAC models establishment and used software-simulation toolkits selection play a key role in the entire system performances evaluation. Of course, there are on the market a wide range of currently available products, ranging from spread-sheet tools to special-purpose tools, or tools that integrate multiple aspects of HVAC systems modeling and simulation [3, 4]. There is no enough space here to enumerate or discuss all these toolkits. However, is outlined that the current fourth generation tools tend to be

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fully integrated with respect to different intelligent buildings performance aspects, such as automate monitoring and supervising, application quality control, intelligent user interfaces, fault-diagnosis, etc. Unfortunately, even at this last-generation level there it seems that some basic HVAC element or component models are not enough well established and developed yet, or fully clarified.

II. BACKGOUND AND IFRASTURCTURE OF THE RESEARCH AND DEVELOPMENT

For the research and development activities unfolded in this paper it is available the entire Building Mechatronics Research Centre of the Electrical Engineering and Mechatronics Department from Debrecen University. There it has been implemented an intelligent building infrastructure, as shown below in "Fig. 1" [5].

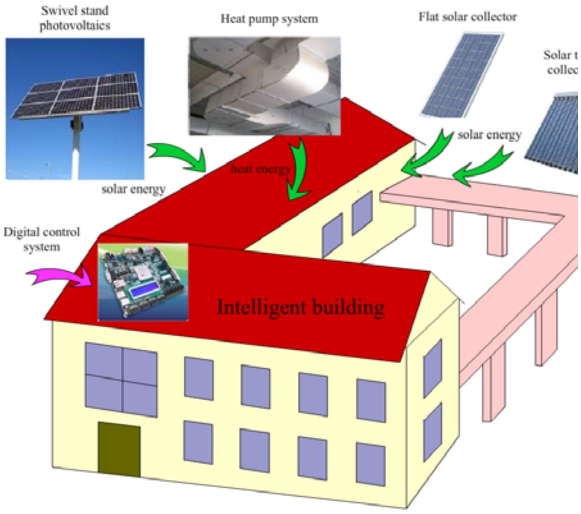

Figure 1. Intelligent building infrastructure developed at the Building Mechatronics Research Centre, Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University.

This building embeds building automation and HVAC control systems, climate control and lighting technologies, a building security and supervising system, the energy supply and its control systems, sensor systems, data acquisition and data processing systems, computer networks, and renewable energy sources. One of the used renewable energy sources is the locally available solar energy captured by using flat solar energy collector and solar tube collector batteries installed on the building's back terrace ("Fig. 2"), and from a swivel-stand photovoltaic battery mounted in the building's garden shown in "Fig. 3" [6]. Additionally, a high capacity heat pump system will provide heat energy stored in several hot water tanks mounted in the intelligent building's basement. The heat pump system and its control board it is presented in "Fig. 4" [7]. There in the building's ceiling has been mounted the duct system with the adequate pipes, and into a cupboard are fixed the heat pump's condenser, the evaporator, the expansion valve, and the compressor. The cupboard also contains the digital control unit developed upon a Programmable Logic Controller-based (PLC) master-slave configuration, the touch-panel

Figure 2. Solar tube collector and flat solar energy collector installed at the Building Mechatronics Research Centre, (Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University).

Figure 3. Swivel-stand photovoltaic battery mounted in the building's garden, (Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University).

Figure 4. The heat pump system installed at the Building Mechatronics Research Centre, (Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University)

Figure 5. Water buffer tank installed at the Building Mechatronics Research Centre, (Department of Electrical Engineering and Mechatronics, Faculty of Engineering, Debrecen University) Produced by the Hajdú Kft.

board for control and settings operations, a measurement system, and a part of the hydraulic system. One of the 750l storage capacity hot water tanks mounted in the intelligent building's basement for heat energy storage purposes is shown in "Fig. 5".

By using net-zero energy strategies, it is proposed that the yearly energy consumption of this building (the Building Mechatronics Research Centre) to be fully covered from the above mentioned locally available renewable non-polluting energy sources. The first major obstacle in this endeavour is that there are no available for this research purposes the adequate software toolkits to simulate the above ranked energy conversion systems in order to evaluate their efficiency, its estimated energy consumptions, the supposed energy fluxes, or the obtained renewable energy amount. Additionally, there are not clear models developed even for basic elements such as the buffer tanks, photovoltaic cell batteries, heating elements, etc. Therefore, it looks quite difficult to design and implement the adequate data acquisition and digital control systems to supervise the entire renewable energy conversion processes. In this circumstance, the best solution seems to be the elaboration of the adequate mathematical models for these elements and to implement it in a next step into software models.

III. HVAC ELEMENTS MATHEMATICAL MODEL DEVELOPMENT

Store elements such as water tanks, liquid reservoirs, or gas containers being basic elements in HVAC systems development and implementation let's consider now for study and analysis the general case of the buffer tank shown in "Fig. 5". For this recipient can be attached the simple block diagram given in "Fig. 6". There are labeled with *Fi* [m^3/s] the input material flux (water, gas, chemical liquid, etc.), with *Fo* [m^3/s] the output material flux, and with Q [m^3] the quantity of the stored material in the recipient. It is no difficult to observe that the stockpile of such a simple store element it changes according to the following rule:

Figure 6. The model of a simple store element in a HVAC system. This can be a water tank, liquid reservoir, gas container, etc.

$$dQ \; = [F_i(t) - F_o(t)]dt. \tag{1}$$

Integrating the stored material quantity, results the relation:

$$Q(t) = Q_o + \int_0^t [F_i(t) - F_o(t)] \cdot dt \, , \tag{2}$$

where Q_o represents the initial material quantity stored in the recipient. This mathematical relation denotes that a storage operation has a purely integration character. Supposing that in our case in the buffer tank hot water will be stored, it is possible to calculate the heat amount stacked there:

$$Q \; = m \cdot c \cdot dt = m \cdot c \cdot (T_w - T_e) \, , \tag{3}$$

where m represents the mass of the stored water, c=4183 J/(kg·K) is the specific heat capacity, T_e represents the environment temperature, and T_w is the stored water temperature. At the same time, using the catalogue parameters of the tank it is possible to calculate the estimated heat energy losses, and to measure the input/output water temperatures and pressures.

In order to more closely imitate the concrete situations in HVAC systems, the simple storage element from "Fig. 6" will be modified into a simultaneous filling and empting open tank, as is expressed below in "Fig. 7".

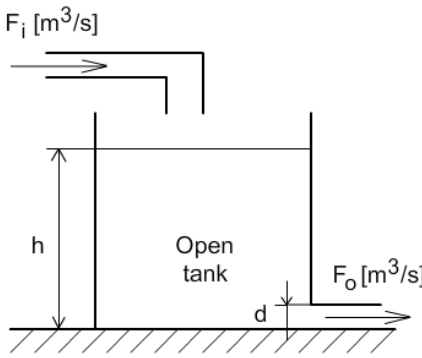

Figure 7. The model of a simultaneously filling and empting open tank in a HVAC system.

There the liquid level available in the tank is labeled with h, the cross-section of the output (or empting) pipe with d, and f is a flow-out coefficient which depends by the stored liquid properties. It is easy to downstate that the output liquid flux is function of the following simple equation:

$$F_o = f \cdot d \cdot \sqrt{2 \cdot g \cdot h}\,, \tag{4}$$

where g is the gravitation constant. The dynamic state-function of the tank will be expressed by the next relation:

$$(F_i - F_o) \cdot dt \ = S \cdot dh\,, \tag{5}$$

the notation S representing the cross-section square of the considered liquid tank. Introducing the constant $k=f \cdot d \cdot (2 \cdot g)^{1/2}$, the equation 5 turns into the expression:

$$dh \cdot S = \left(F_i - k \cdot \sqrt{h}\right) \cdot dt\,. \tag{6}$$

It is self-understanding that in order to determine the h liquid level at given t moment, the differential equation expressed in the relation (6) must be solved. Unfolding the nonlinear $\sqrt{h}$ function into Taylor series and considering only its two first elements, results that:

$$\sqrt{h} \ \cong \ \sqrt{h_0} + (h - h_0)/(2\sqrt{h_0}\,)\,, \tag{7}$$

the constant h_0 expressing the initial liquid level in the tank. Substituting equation (7) into the relation (6), results an equation in the following form:

$$dh \ = \ (a - b \cdot h) \cdot dt\,, \tag{8}$$

with the solution expressed as:

$$h = (a - e^{-b \cdot t})/b\,. \tag{9}$$

where a=F_i/S - k·sqrt(h_0)/2S, and b=k/[2S·sqrt(h_0)].

The above presented equation-set (2), (6), and (9) constitute the mathematical support for novel LabView software-based store element models development and implementation. Another important element in HVAC systems is the flow tanks under pressure. This is a closed tank where the volume upper the water level is completed by a gas under pressure ("Fig. 8").

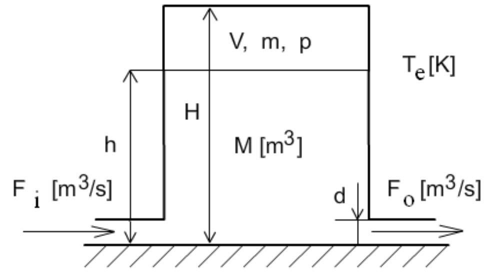

Figure 8. The model of a flow tank under pressure in a HVAC system.

According to the general gas law, for a gas with G specific constant, V volume, mass m, and p pressure it is possible to write the mathematical relation:

$$p \cdot V \ = \ m \cdot G \cdot T\,. \tag{10}$$

Considering the tank's H and h dimensions:

$$p \cdot (H - h) \cdot S \ = \ m \cdot G \cdot T\,, \tag{11}$$

resulting

$$p \ = \ m \cdot G \cdot T/[(H - h) \cdot S]\,, \tag{12}$$

where S represents the cross-section surface of the considered tank. At the same time, the output material flux can be expressed with the relation [8]:

$$F_{ki} = f \cdot d \cdot \sqrt{2 \cdot g \cdot (h + p/n)}\,, \tag{13}$$

where n represents the specific gravity of the liquid stored in the tank. Substituting the above equation the relation (12), it is obtained:

$$F_o = f \cdot d \cdot \sqrt{2 \cdot g \cdot (h + (m \cdot G \cdot T)/(n \cdot S \cdot (H - h)))}\,. \tag{14}$$

It is also valid the well known dynamic state equation

$$(F_i - F_o) \cdot dt \ = S \cdot dh\,,$$

In which it is possible to substitute the relationship 14. Results that:

$$[F_i - f \cdot d \cdot \sqrt{2 \cdot g \cdot (h + (m \cdot G \cdot T)/(n \cdot S \cdot (H - h)))}]dt = S \cdot dh\,, \tag{15}$$

In the above expressed differential equation the unknown variable is the h magnitude, and the equation can be solved in a similar way than in case of the simultaneous filling and empting open tank [8].

In HVAC systems development and implementation the different types of material mixers also plays an important role. Let's consider for example the case marked in "Fig. 9", where a recipient mixing 3 different type input materials is expressed.

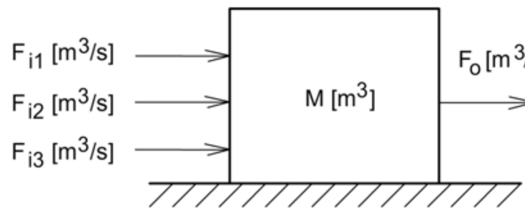

Figure 9. The model of a simple mixer

It is self-understanding that the mass of the material stored in the recipient it is equal with the sum of the three component materials masses:

$$M = \ M_1 + \ M_2 + M_3\,. \tag{16}$$

The concentration of each component k_i $(i=1\div3)$ can be calculated with the simple relations:

$$k_1 \ = M_1/M\,, \quad k_2 \ = M_2/M\,, \quad k_3 \ = M_3/M\,. \tag{17}$$

These concentrations are suitable to be also expressed with the input- and output material fluxes:

$$k_1 = F_{i1}/F_o\,, \qquad k_2 = F_{i2}/F_o, \qquad k_3 = F_{i3}/F_o\,. \tag{18}$$

If an input material flux is changing over time, the concentration of this material in the tank also will change. This process it is described by the following differential relationship:

$$dM_i = [F_{ii}(t) - F_{oi}(t)] \cdot dt\,, (i = 1 \div 3) \tag{19}$$

or

$$M \cdot dc_i = [F_{ii}(t) - F_{oi}(t)] \cdot dt\,, \tag{20}$$

Because the input- and output fluxes are also the same in the transition process, it can be stated that [8]:

$$M \cdot dc_i = F_o \cdot [c_{ii}(t) - c_{oi}(t)] \cdot dt\,. \tag{21}$$

Supposing an ideal mixing process, results:

$$M \cdot dc_i = F_o \cdot [c_{ii}(t) - c_i(t)] \cdot dt\,. \tag{22}$$

The above expressed mathematical relation makes possible the calculation of the concentration time-diagram of component *i* $(i=1\div3)$. Solving the equation 22, results that the c_i concentration has an exponential variation, with the time constant $T=M/F_{ki}$.

In a similar way like above has been expressed it is possible to develop models for other HVAC elements like heating elements, fan coils, other type of store elements, tanks, reservoirs, etc.

IV. HVAC Models LabView-Based Software Implementation

The mathematical models established in the previous paragraph constitute an adequate background for novel software developments and HVAC simulation means implementation. In this research effort it has been considered that the best selection for our purposes it looks the graphical oriented LabView software toolkit utilization, which allows the creation of the so called "Virtual Instruments" (VIs) as independent and versatile graphical program units. For the first implementation example let's consider the mathematical model of the simultaneously filling and empting open tank in a HVAC system described by the equations (5), (6), and (9). Then it is considered an arbitrary large store element as shown in the LabView Front Panel from "Fig. 10", which can represent a wide range of components, such as a water tank, a liquid reservoir, a gas container, etc. In the figure the particular case of a water tank has been considered, with its two initial dimensions: the tank volume and its cross-section surface. At the same time, at the beginning of the storage process the tank can be empty, or even with an initial quantity of material (in this case water), expressed here by the V_o variable. The input water flux *Fi* [m^3/s] is generated by the *Input pump*, via an *Input pipe,* and *Input valve,* being controlled through a numerical slide-bar labeled here *Input flux*. The green colors indicate that the *Input pump* is working and the *Input valve* is open (red color means that these are closed). At the same time, the blue color of the *Input pipe* indicates a water flow otherwise the pipe is empty.

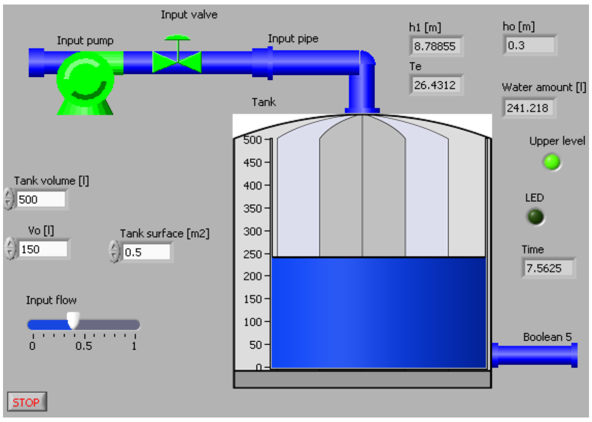

Figure 10. The LabView model of a simultaneously filling and empting open tank in a HVAC system.

The empting pipe of the tank is represented by the *Boolean_5* variable in the figure. There continuously flows out the water quantity F_o calculated with the nonlinear relationship (4). The dynamic state function which expresses the difference between the input water flux *Fi* and the output flux F_o describes the operation mode of this tank, as shown in the equation (5). The solution of this equation points that if the input water flux is changing the water level will follow different exponential curves. Therefore, for a set of different values of the *Input flux* slide bar (marked by the LED indicator), a family of exponential curves will be obtained, with variable constant times (labeled with T_e on the panel).

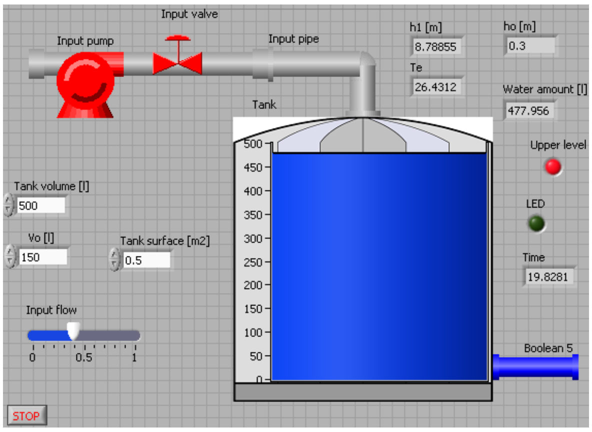

Figure 11. The operating mode of a simultaneously filling and empting open tank in a HVAC system.

Reaching the imposed maximal water level the filling operation of the tank is stopped as is shown in "Fig. 11".

A piece of the LabView Block Diagram program designed for the simultaneously filling and empting open tank model is given in "Fig. 12". There it can be followed in the *Equation* VI, respectively in *Formula_3*, *Formula_4*, and *Formula_5* VIs the implemented mathematical relationships for the tank model. The *Elapsed Time* VI it has been used for integration operations echievment.

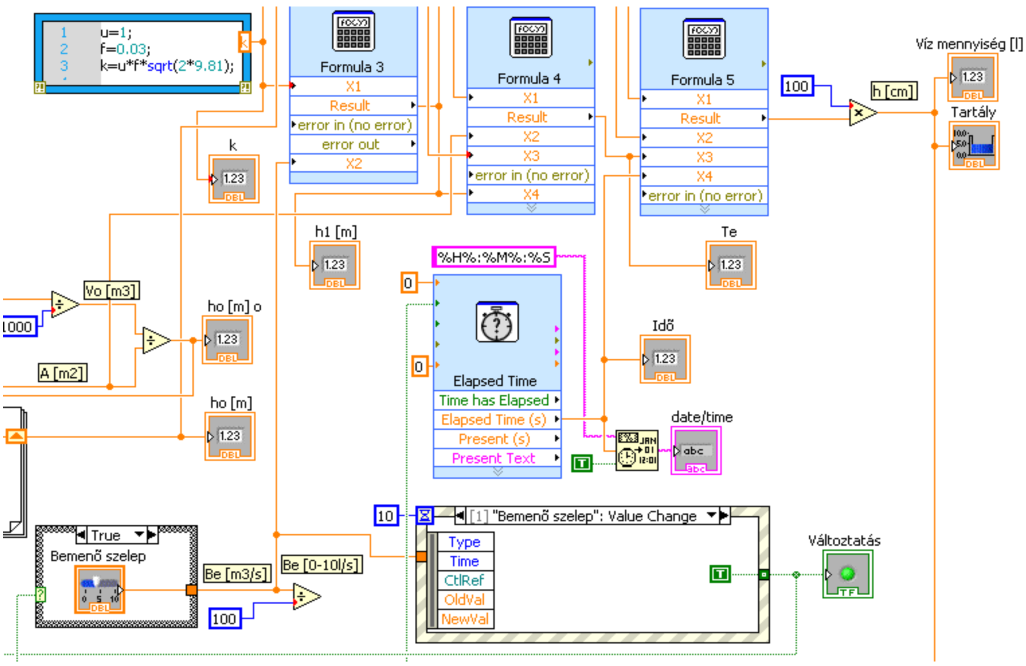

Figure 12. The operating mode of a simultaneously filling and empting open tank in a HVAC system (a piece of the LabView Block Diagram).

Hereinafter, the *Event Capture* VI follows the F_i input water flux change over time and a LED indicator blinks if a different water flux rate has been detected. Other mathematical operator VIs shown in the diagram performs the elementary algebraic operations. However, similar LabView software-based models can be designed and implemented in the same way for all the mathematical models indicated in the 3rd paragraph. Each own of these constitute a new VI which can be then provided with the adequate specific VI icon and interfaced with communication lines and buses.

V. CONCLUSIONS

The paper presents research and development efforts regarding the HVAC elements modeling and simulation for net-zero energy building applications. As a part of a long-term research project, in this stage the basic goal is to develop a complex LabView graphical oriented software-based modeling and simulation system suitable to follow and monitor complex HVAC processes in intelligent buildings. The Building Mechatronics Research Centre of the Electrical Engineering and Mechatronics Department from Debrecen University has been specially designed and conceived as an intelligent building using renewable energy sources. There the basic aim is to cover the buildings annually energy needs from locally available non-polluting sources. Therefore, the elaborated novel models will be integrated later into a complex automation system designed to reach the net-zero energy building goal. In this stage it can be concluded that the elaborated models and toolkits are in a right way designed and implemented, exhibiting sufficient flexibility and versatility for future developments and implementation in complex HVAC systems.

ACKNOWLEDGMENT

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