Hardware-in-the-Loop Platform for Performance Evaluation of Energy Production, Storage and Distribution Systems for Buildings

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RESUME. Le présent travail effectué dans le cadre du projet PEPSE (Poste d'Essai « semi-virtuel » pour le test de systèmes de Production, de Stockage et de distribution d'Energie) vise à concevoir, développer et à mettre en place l'infrastructure et l'équipement d'un laboratoire pour évaluer les performances énergétiques des systèmes de production, de stockage et de distribution de chaleur et de froid dans les bâtiments. La plateforme est semi-virtuelle, c'est-à-dire que les sources/charges d'énergie peuvent être réelles ou simulées. L'environnement virtuel (qui est un programme numérique de simulation des sources/charges d'énergie) contrôle les conditions d'entrées et le fonctionnement du dispositif testé par le biais d'une ou de plusieurs unités satellite (c-à-d. les interfaces physiques) situées sur les lignes de départ et de retour des boucles hydrauliques/aérauliques. Les conditions à la sortie de l'équipement à tester sont également renvoyées vers le programme de simulation par ces interfaces. Ces dernières sont alimentées en eau chaude et froide par deux systèmes de production et de distribution d'énergie. La puissance maximale des appareils à tester pourrait atteindre 200 kW (en chaud ou en froid). Cette capacité permet au laboratoire de tester une gamme relativement large d'appareils allant de ceux de chauffage ou de refroidissement d'une maison individuelle aux équipements / systèmes énergétiques d'un bâtiment résidentiel multifamilial ou aux équipements de chauffage urbain, etc.

MOTS-CLÉS : simulation thermique dynamique, système énergétique, plateforme semi-virtuelle.

ABSTRACT. The current study carried out within the framework of the PEPSE (Semi-virtual Platform for performance Evaluation of Energy Production, Storage and distribution systems for buildings) project aims at designing, developing and setting up the infrastructure and the equipment of a laboratory for evaluating the energy performance of heating and cooling production, storage and distribution systems in buildings. The platform is semi-virtual, i.e. energy sources and loads can be real or simulated. The virtual environment (which is a numerical program for simulating energy sources and loads) controls the inlet conditions and the operation of tested device by means of one or several satellite units (i.e. physical interfaces) located on the distribution and return lines of the hydraulic/air-flow loops. The equipment outlet conditions are also sent back towards the simulation program by these interfaces. The latter are supplied with hot and cold water by two energy production and distribution systems. The maximum power of devices to be tested could be up to 200 kW (heating or cooling). This capacity allows the laboratory to test a relatively wide range of devices from the heating or cooling appliances of a single-family house to the energy equipment/system of multi-family residential building or the equipment for district heating system, etc.

KEYWORDS: dynamic simulation, building energy system, hardware-in-the-loop.

1. INTRODUCTION

The building energy performance, the occupant comfort requirements, the exploitation of renewable energy sources and the technical possibilities have greatly evolved in recent years. The improvement in building isolation has led to a reduction in heating needs (reduction in heating power and distribution temperature) while domestic hot water (DHW) needs are increasing (increase in heating power or volume storage). The growing use of renewable energies is accompanied by a need to regulate this variable intake (over a day as over a season). The availability of more modern technologies (heat pumps, fuel cells,...), the possibility of combining these technologies, the storage of energy in new forms, the intelligent use of it and the possibility to export excess energy to a distribution network (electricity, heat) are recent solutions which should be further studied. The combination of several systems is promising in terms of energy but requires appropriate regulation to effectively benefit from the advantages of each technique. Determining which existing system is best suited for the desired application and specifically developing new systems are the challenges that must be met to ensure the energy efficiency of buildings in the future.

Indeed, the necessity of innovation on this field requires the industry to develop faster and faster new products while ensuring a good quality (in terms of energy performance) of the products. Prototypes and later the final product must be developed and tested. The annual performances of the systems have to be estimated (Riederer, Partenay, and Raguideau 2009). Several modelling and simulation techniques can be used to evaluate HVAC equipment performance (Byrne, Miriel, and Lénat 2012). However, experimental validation is almost always required to determine the actual system performance. As the operating conditions for HVAC equipment are so varied, characterizing performance by field testing is both impractical and unrealistic. To overcome this issue, hardware-in-the loop (HIL) simulation (also called emulation technique) can be used. Indeed, the hardware-in-the-loop simulation is frequently used in the development and testing of complex real-time embedded systems to reduce testing cost and provide a more flexible and controlled testing environment (Macdonald et al. 2014). The great advantage of this technique is to be able to test different devices under real operating conditions without having to physically have the building in which these devices are placed and with which they interact. The behavior of the building environment and its interactions with the equipment to be tested is thus reproduced virtually by numerical simulation. Different situations and parameters can thus be assessed such as the impact of the building's characteristics (type, energy class), the influence of weather conditions (season, month, time of day), the influence of the occupancy rate, building usage mode. In addition, the emulation also relates to the other equipment of the buildings which could interact with the equipment to be tested such as for example solar panels (electric or thermal), heating circuits (radiators, circulator, storage tank, etc.), ventilation, DHW production. It will therefore be possible with the bench to assess the energy performance and robustness of the equipment in a controlled, rapid and inexpensive manner and this in the various phases of development of the equipment.

Many laboratories employ today the emulation technique to evaluate the performance of energy system/equipment in the buildings. Both Semi-Virtual Energy Integration Laboratory (Waddicor et al. 2016) and Smart Energy Laboratory (Kim, Del-Rosario-Calaf, and Norford 2017) managed by Catalonia Institute for Energy Research used HIL technique for assessing the development and integration of renewable energy solutions and innovative thermal and electrical equipment that are designed to improve energy efficiency in building and energy system. The nearly zero energy building emulator platform (Ruusu et al. 2016) developed by Aalto University is designed for studying the performance of a building with different renewable energy production and storage equipment. The actual building is a TRNSYS (Klein, S.A. et al 2017) simulation running in a computer and the physical devices are operated according to electricity and heating demands given by the simulation at 6-minutes (changeable) intervals. The OPSYS (Combined OPtimization of heat pumps and heat emitting SYStems) test rig managed by Danish Technological Institute emulates a house with an underfloor heating system to which a ground source heat pump can be connected. Semi-virtual laboratory (Macdonald et al. 2014) of Polytechnique Montreal allows to perform hardware-in-the-loop testing, where HVAC equipment is tested in realistic operating conditions provided by a full system dynamic simulation with the TRNSYS program. The semi-virtual platform PEPSY (Riederer, Partenay, and Raguideau 2009) managed by CSTB has been developed for testing renewable thermal energy systems. The platform is based on system simulation and allows the performance evaluation of many systems such as solar DHW systems, solar combi-systems or ground source heat pump systems, etc.

Within this context, the semi-virtual platform PEPSE would be designed as a modern and efficient tool intended to be made available to internal and external research teams of the laboratory as well as companies in the sector for testing or developing new products. The emulation technique, physical interface (also called satellite unit) would be the key components allowing the laboratory to test a relatively wide range of devices from the heating or cooling appliances of a single-family house to the energy equipment/system of multi-family residential building or the equipment for district heating system, etc.

2. PEPSE CONCEPT

2.1. THE LABORATORY INFRASTRUCTURE

The concept of the laboratory is found in Figure 1. The principle of this semi-virtual platform is to integrate the product to be tested in a virtual environment. The tested device is connected to the virtual part (numerical model of the test environment) via one or more physical interfaces (part of physical laboratory equipment) supplied with hot and cold water by two systems of production and distribution of energy. These interfaces consist of hydraulic, measurement and control equipment (i.e. pump, mixing valves, heat exchanger, electrical resistance and supervisory control and data acquisition system as found in Figure 2) allowing to control as precisely as possible the flowrate and temperature of the fluid entering the tested device. The fact that the physical interfaces are modulable and mobile makes it very easy to install and configure the equipment and to be able to carry out many tests in parallel. A number of mobile energy recovery loops will also be set up permitting to recover any energy generated during the test for heating up the laboratory or to produce DHW.

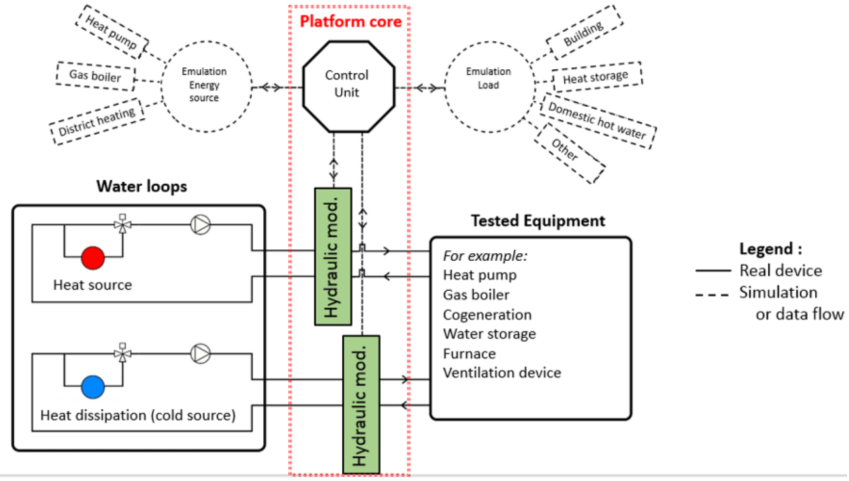

Figure 1: PEPSE concept

The virtual environment (i.e. TRNSYS model) corresponds to the building and its energy distribution system/equipment, occupant and internal load, etc. For the first time, the software package TRNSYS will be used during the test to perform real-time system dynamic simulation thanks to its flexibility, modularity and the availability of many built-in components for building energy simulation. Other simulators could also be considered according to the demand of the test in the next step of the project.

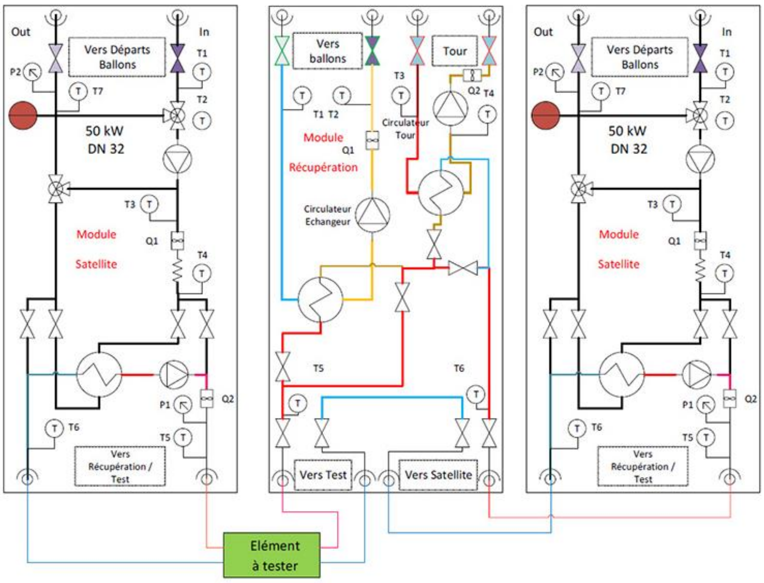

Figure 2 : A possible connection between satellite units (right and left), recovery unit (middle) and tested device

Regarding energy production and distribution systems of the laboratory, it mainly includes boilers and refrigeration machines as well as hot water and chilled water tanks. The use of storage tanks and appropriate regulation allows supplying downstream applications at a stable temperature. The energy flux can be distributed to many satellite units via three circuits along the length of the building (two circuits for hot water and one for chilled water). Along these circuits, many drawing points allow the connection of satellite units. The climatic chambers with air handling unit are also available permitting the laboratory to perform the tests of more different kinds of energy system/equipment.

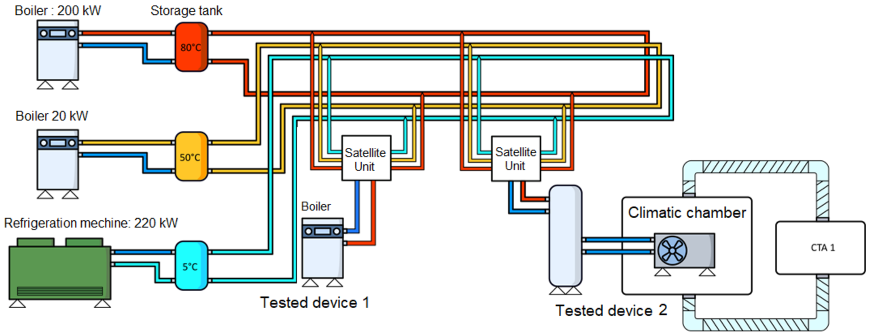

Figure 3: Laboratory infrastructure

2.2. REAL TO VIRTUAL INTERFACE

The communication between the SCADA (Supervisory Control and Data Acquisition) system of the satellite unit and the virtual environment is described in Figure 4. This quasi-synchronous communication is carried out using two shared text files, e.g. “tolabwindow.txt” and “fromlabwindow.txt”. At each test time step, the data acquisition and control system (e.g. LabWindows) controls, using pump, mixing valves, and the electrical resistance of the physical interface, the temperature and the flowrate of fluid entering the tested device according to the values found in the file “tolabwindow.txt”. At the same time, the SCADA system measures the value of temperature and flowrate of the fluid exiting the tested device and save these data together with other possible data (e.g. information about test) in the file “fromlabwindow.txt”. The simulator meanwhile at each time step of the simulation opens the file “fromlabwindow.txt”, supplies the numerical model with the obtained data, performs the numerical calculation and updates the values in the file “tolabwindow.txt”.

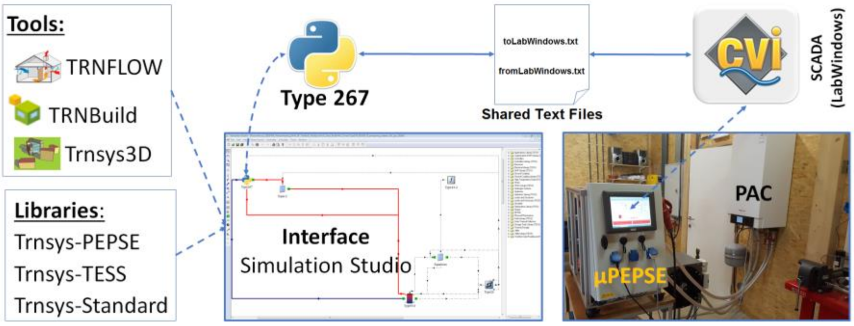

Figure 4 : TRNSYS-python coupling

The TRNSYS-python coupling is used for reading and updating shared text files at each time step of the test. Indeed, the use of python facilitates reading/writing data from text file and handling possible errors occurs during test. A specific TRNSYS component (Type 267) based on Type 169 of the standard TRNSYS library is developed and dedicated to the TRNSYS-python coupling. A TRNSYS library (TRNSYS-PEPSE) dedicated to PEPSE platform will be also developed. This library will include the components which do not exist in existing TRNSYS libraries (TRNSYS-Standard, TRNSYS-TESS) but are required for the test, and a number of preconfigured global TRNSYS models for several possible test scenarios.

3. CASE STUDY USING µPEPSE MODULE

To demonstrate the validity of platform concept, it was decided to develop a satellite module at a reduced power of 10 kW (called µPEPSE) and to operate this module in an existing laboratory (i.e. Jacques Geelen Laboratory of the University of Liège). This µPEPSE was then used to evaluate the performance of a 10-kW air-water heat pump for space heating and DHW preparation of a single-family house whose numerical model is described in the reference (Le et al. 2019). The test is carried out for 24 hours of a winter day (i.e 13th January). The weather data come from the typical meteorological year (TMY2) data of Uccle in Belgium.

As found in Figure 5, the simulation environment (right) communicates with the experimental one (left) using TRNSYS-python coupling. For the current test, the heat pump (tested device) is combined with the solar thermal collectors (virtual components) for charging a buffer storage tank (virtual component). The operation of the heat pump and of the solar panels is controlled according to the temperature of the water inside the virtual storage tank. Within the virtual environment, the space heating loop is connected directly to the buffer tank and controlled by the room thermostat located in the living-room. To produce DHW, the cold water goes through the coiled tube heat exchanger inside the storage tank to increase the temperature. The hot water exiting the coil will then be mixed with the cold water to yield hot water at the desired temperature.

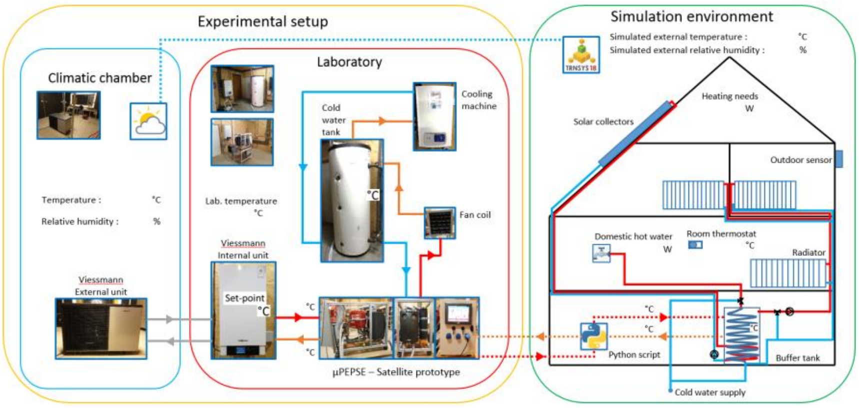

Figure 5 : Implementation of µPEPSE for testing an air-water heat pump

When the test is launched, the water is pumped from the cold-water tank towards the satellite module. The temperature of the water entering the heat pump is controlled by SCADA system of satellite module according to the temperature of the water leaving the (virtual) storage tank in the house. The temperature and flowrate of the water leaving the (real) heat pump are measured and sent back to the simulation environment. The hot water exiting the heat pump is cooled down before stored in the cold-water tank. As the objective of this test is to demonstrate the concept of coupling between the real part and the emulated part. A simple accelerated control strategy was used as follows:

- If the temperature of water inside virtual storage tank is lower than 40 °C: the heat pump is ON
- If the temperature of water inside virtual storage tank is higher than 42 °C: the heat pump is OFF

In Figure 6, the (real) ON/OFF of the heat pump, corresponding to the (real) water flowrate (in continuous green), follows well the control ON/OFF (in dotted green) coming from the simulation environment. A positive water flowrate means that the heat pump is ON and a zero flowrate, the heat pump is OFF. When the heat pump is ON, the temperature, controlled by the satellite module, of the water (in continuous blue) entering the heat pump is in good agreement with the temperature (in dotted red) of water coming out from the house's (virtual) storage tank.

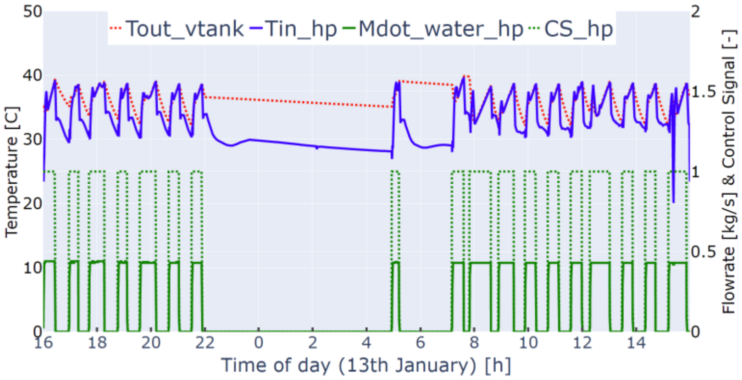

Figure 6: Real heat pump ON/OFF & inlet temperature and their virtual corresponding values

As found in Figure 7, the house heating (for studied day) is guaranteed. The temperature (continuous pink curve) of the living room follows well the set values (dotted pink curve) of the living room thermostat) while the desired DHW temperature (in continuous brown), i.e. 45 °C, cannot be reached due to the relatively low temperature of the water in the (virtual) storage tank (in continuous red). This is the consequence of the involved control strategy and the fact that the current heat pump cannot heat water up to a temperature above 50 °C. An additional source will be necessary for the DHW production, or another system configuration should be used for space heating and DHW preparation of the studied house.

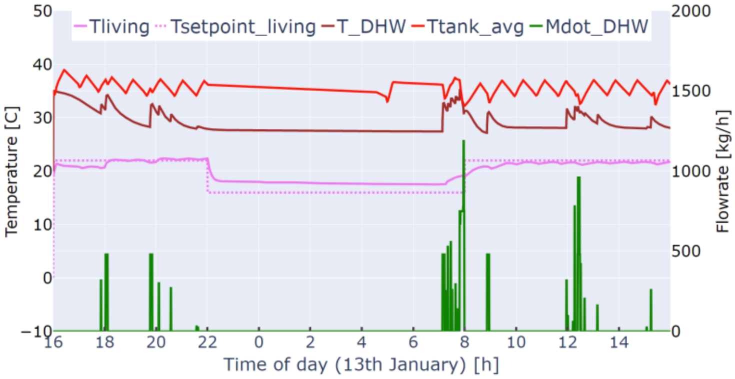

Figure 7 : House thermal comfort and domestic hot water preparation

The lower part of Figure 8 shows the space heating and DHW needs of the house during the studied day. While the power required for heating is relatively low and continuously between 8h and 22h. the power demanded in terms of DHW is high and discontinuous. In the upper part of Figure 8, the heat pump operates intermittently to maintain the set temperature in the (virtual) storage tank. Its power is around 10 kW and the coefficient of performance is between 3 and 4 in operation.

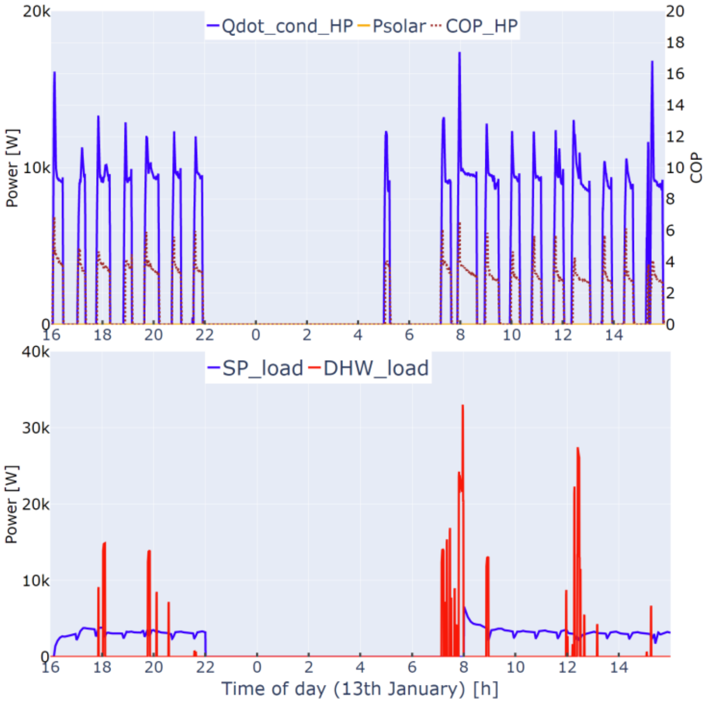

Figure 8 : Virtual space heating and DHW demand & real heat pump performances

4. CONCLUSIONS

This study introduces the overall concept and the implementation stages of a semi-virtual platform to assess the performance of energy equipment/systems in buildings. The platform uses the emulation technique to evaluate the performance of the device to be tested in a transient regime within its whole environment (i.e. the building and in connection with other virtual/real components). The use of modular and mobile satellite modules facilitates the installation of the test bench and reduces the time for the test configuration. A satellite module at a reduced power of 10 kW (called µPEPSE) is developed. This µPEPSE is then used to assess the performance of a 10-kW air-water heat pump for space heating and DHW preparation of a single-family house. The initial result shows that the concept of the platform working well. This is the premise for the implementation of the full-scale platform PEPSE in the future. Many lessons learnt from this study would be useful for the development of the virtual part as well as the real part of the platform.

5. ACKNOWLEDGEMENT

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