FOG

Workpackage n° 7 final report

"Construction of a prototype environmental chamber"

GROWTH contract n° G6RD-CT-2000-00211

Improvement of transport safety by control of fog production in a chamber

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IMPROVEMENT OF TRANSPORT SAFETY BY CONTROL OF FOG PRODUCTION IN A CHAMBER

WP7 final report

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Executive Publishable Summary of the Fog project

Background

In the field of transportation, ever increasing attention is dedicated to systems and methodologies suitable for active safety functions and driver assistance applications on vehicles. Testing these systems in low visibility conditions is critical but difficult, if not impossible to carry out in real road conditions, specially in presence of fog. To overcome these barriers, a specific fog testing centre is required. Some artificial "fog chambers" exist (one example is located owned by CETE-Lyon in Clermont-Ferrand), but their operation and behaviour appear as far from optimal.

Objectives

This project intended to address the challenge of designing a new concept of fog chamber by, first, elaborating a scale-model prototype, which will integrate a number of advanced technologies :

- fog production device and associated fog stabilization process
- visibility measurement technique
- heating, ventilation and air-conditioning equipment and associated control system

Furthermore, the design of the prototype has been assisted by the development of an enhanced simulation model. At the end of the project, the performance of the scale-model prototype will allow to set up the specifications of a future real-scale fog chamber.

The efficiency of the new concept was evaluated through the quality (opacity and similarity with "natural" fog characteristics) as well as the duration (control) of the low visibility conditions no matter what the ambient conditions are.

Work programme

The project was divided in eight work-packages. Each work-package is under responsability of one specific partner :

1. State-of-the-art : to insure a good background and communication between partners
2. Development of a simulation model (resp. University of Strathclyde)
3. Development of an innovative fog production device (resp. CETE Lyon)
4. Development of an innovative visibility measurement method (resp. CSEM Neuchâtel)
5. Development of the conditioning and control equipment (resp. University of Liège)
6. Design and test of safety studies experimentation (resp. INRETS)
7. Construction of a prototype of fog chamber (resp. FUL)
8. Formulation of specifications for a real size fog chamber (resp. CRF)

The duration of the project was three years. All developed equipment should be available at the end of the second year while the third year should be reserved for intensive testing.

Organisation

Eight working meetings held : Clermont-Ferrand (05/00), Liège (11/00), Glasgow (05/01), Arlon (mid-term) (09/01), Torino (03/02), Saint-Paul (11/02), Paris (01/03), Neuchatel (02/03)

0. Summary

The central objective of the FOG project was to build a reduced scale fog chamber including some innovative features : fog production system, laser-based visibility measurement system, heating, ventilating and cooling equipment including control system. For practical reasons, the project involved the construction of a totally new building on the FUL campus to host the fog chamber. The design and construction of this building was carried out following a classical engineering approach including the following steps: formulation of specifications, design, construction, commissioning, testing and operation. The successive design phases were additionally supported by the use of modern simulation tools. The purpose of this report is to give an overview of the selection of the different design options realized during this project, to summarize and illustrate the construction process and to provide the results of the first experimental testing phase conducted in the building.

In order to realize this construction work, a number of "strategic" choices were realized at the begin of the project:

- adoption of a professional building design approach
- use of a global environmental approach
- use of modern simulation tools in the design process.

The professional building design approach included the traditional steps in such a process: conceptual design, preliminary design, detailed design, construction and commissioning, operation and testing. Most of the phases were supported by the use of modern building simulation tools (ESP-r and TRNSYS). This was applied to the design and development of the building, HVAC system (including control) as well as for the construction of the climate chamber hosting fog production experimentations.

The results of this work is now fully operational, as the conclusion of a continuous 2 years process, with the usual "problems" occurring in the construction of a building: delays, reorientation of some aspects of the design in the course of the project,…

The construction of the building and of the fog chamber was concluded by a preliminary testing phase that demonstrated the relevancy of the concept. The facility was used as well for final testing of additional deliverables of the project: visibility sensors, testing methodologies, software validation.

As a general conclusion, the main highlighting characteristics of this construction are:

- an improved fog chamber prototype showing efficient climate control
- a flexible testing facility with an unlimited number of potential applications in relation to climate control
- a high-level monitoring and control system with more than 150 sensors connected
- an ecological modern building ready for demonstration and visits, including the use of natural energy sources and material

As announced right from the start in the project proposal, a high number of research applications can benefit from this facility: energy management, air quality and aerosols, bio-indicators and agricultural research.

1. Introduction

The major output of the FOG project is a reduced scale fog chamber including some innovative features : fog production system, laser-based visibility measurement system, heating, ventilating and cooling equipment including control system. The design and construction of this building was carried out following a classical engineering approach including the following steps: formulation of specifications, design, construction, commissioning, testing and operation. The successive design phases were additionnally supported by the use of modern simulation tools. The purpose of this report is to give an overview of the selection of the different design options realized during this project, to summarize and illustrate the construction process and to provide the results of the first experimental testing phase conducted in the building.

2. Specifications

2.1. Introduction

As in the current engineering practice, the building project started with the formulation of the specifications in order to prepare the different calls for tenders. A part of the definition of the specifications of the testing facility was defined in-house while the collaboration of an architect was decided for all aspects related to the construction of the building itself.

Specifications defined by the architect concerned:

- the building infrastructure, including sewage
- the building structure and covering
- the internal partitions, slabs and pavement
- the plumbing and sanitary equipment

In-house defined specifications concerned:

- the Heating, Ventilation and Air Conditioning (HVAC) climate control system
- the fog production system
- the monitoring and control system
- the electrical system

2.2. Specifications of the testing facility construction

The specifications of the construction of the building were prepared by the architect in charge of the project (Mr Olivier LOMMEL). This work resulted in a document including the following chapters and available in french.

A. Administrative matters
B. Technical matters

- Sewage and foundations
- Building structure and covering
- Internal ground slab
- Sanitary accessories and plumbing

2.3. Equipment of the building

Given the research objectives of the project, the testing facility will host equipment in order to :

- generate artificial fog
- control the internal climate inside the faciltiy

Each of these aspects gives rise to a specific equipment

2.3.1. Climate control systems

The function of a climate control system is to maintain a given internal climate in terms of temperature, relative humidity, air velocity. Therefore, the facility is provided with two different systems:

- an air-based system (ventilation) - low inertia system
- a radiant system (floor and ceiling) – high inertia system

Upstream of these energy distribution systems, the facility should be connected to two different sources: solar source and ambient air (by means of a heat pump)

2.3.1.1. Ventilation system

The ventilation system contributes to both heating and cooling of the facility. It is made of a fan, a cooling coil, a heating coil and a filter. In heating mode, the air is heated by the heating coil connected to a storage tank heated by the solar collectors or by the heatpump. In cooling mode, the air is cooled by a cooling coil connected to a cold water storage tank which is cooled down by the evaporator of the heat pump.

2.3.1.2. Radiant system

The radiant system includes a floor and a ceiling which can be connected to the heating circuit (primary source = solar collector or condenser of the heat pump) or to the cooling circuit (primary source = evaporator of the heat pump)

2.3.2. Fog production system

Fog production should be realized by a system similar to the one installed in the Clermont-Ferrand fog chamber. This system is made of a tank (250l), a filtration system, a « demineralisator », a high pressure pump with control and valves feeding a network of copper pipes connected to the injection nozzles.

2.3.3. Electrical equipement

The intended functions of the electrical equipment are the following :

- to supply artificial lighting in the building, specially in the wet conditions of the fog chamber
- to supply power to the HVAC system, specially to the heat pump, which is likely to work as a 3 phases system
- to integrate a solar photovoltaic system and to connect it to the grid
- to supply power to the monitoring system, in particular to some “active” sensors (which consume electricity)

The main constraint on the electrical side comes from the wet (saturated) conditions encountered in the fog chamber which involve the use of IP65 appliances and low voltage.

From the beginning of the project, it was decided to carry out the electrical system design and installation work in-house.

2.4. INSTRUMENTATION OF THE FACILITY

The instrumentation of the facility is obviously connected to the research objectives of the project and the future applications. Both research directions (fog production and climate control) show aspects which require a common instrumentation but they also have specific requirements which involve a dedicated instrumentation.

2.4.1. Common instrumentation "climate control- fog production"

Essentially, the common instrumentation includes measurement of the indoor climate and meteorological conditions.

2.4.1.1. Meteorological conditions

A complete meteorological station is available on the FUL campus and performs a number of measurements including solar radiation. Consequently, for this project, it was only planned to install a minimal meteorological station to measure the micro climate next to the facility or to realize very specific measurements (eg visibility)

The variables to measure next to the facility are:

- ambient air dry temperature
- ambient air wet temperature
- atmospheric pressure
- visibility

Given the characteristics of the site, it was decided not to measure wind velocity nor wind direction while measurement of the different solar radiation components should be taken from the general solar station of FUL located on an other building

2.4.1.2. Indoor climate

The following measurements are required:

- 5 measurement stations performing, at three different heights, measurement of:
    * dry bulb temperature
    * wet bulb température
    * resultant temperature

- surface temperature at the centre of each wall of the chamber
- dry bulb and resultant temperature in the offices and in the technical room
- slab temperature

2.4.2. Specific instrumentation for climate control

This essentially concerns the different heating and cooling systems. The following measurements are required:

2.4.2.1. Ventilation System

- water temperature at the inlet and outlet of the cooling coil
- water temperature at the inlet and outlet of the heating coil (if present)
- water flowrate in the heating and cooling coils circuits
- air temperature at the outlet of the fan
- flowrate of the fan

2.4.2.2. Radiant system

- water temperature at the inlet of the radiating floor and ceiling
- water temperature at the outlet of the radiating floor and ceiling
- water flowrate in the radiating floor

2.4.2.3. Primary solar circuit

- water temperature at the inlet of the solar collectors
- water temperature at the outlet of the solar collectors
- water flowrate of the primary solar circuit

2.4.2.4. Heat pump circuits

- water temperature at the inlet of the condenser
- water temperature at the outlet of the condenser
- water temperature at the inlet of the evaporator
- water temperature at the outlet of the evaporator
- ambient representative temperature

2.4.2.5. Storages

- representative temperatures of the hot water storage
- representative temperatures of the cold water storage

2.4.3. Instrumentation specific to the fog production system

Aside of the thermal measurements listed hereabove, the following specific measurements are required for fog production experimentations.

- visibility measurement in the chamber
- water temperature measurement in the tank containing the water used for fog generation
- water flowrate measurement in the fog production lines or pressure measurement at the outlet of the pump

2.5. Monitoring and control of the facility

The facility includes a monitoring system integrated within a global control software allowing to drive the different technical systems located inside the chamber.

2.5.1. Control of the facilitity

The functions of the control system are to:

- allow the selection of an operating mode:

    * internal climate control

        - radiant systems
        - ventilation systems

- combined action

* fog production without internal climate control

* combined mode: fog production with internal climate control

- when an operating mode is selected, to perform the local control of the actuators concerned by the selected mode in order to maintain the facility at the required setpoint conditions

The control system is based upon a measurement system (including the instrumentation described hereabove). To summarize, the role of the measurement system is twofold:

- to monitor the performances of the facility
- to provide the required informations to the control system

2.5.2. Data acquisition

2.5.2.1. Data acquisition system

The data acquisition system should be a centralised system connected to local controllers. Metrologic performances should be high-level (16 bits coding).

2.5.2.2. Data acquisition software

The functions of the data acquisition software are the following :

- configuration of the measurement channels: type of sensors, sampling rate, archieving rates
- sampling of measurements
- archieving of data
- archieving of messages in a log file
- on-line graphical display of selected measurement channels

3. Design of the building

3.1. The overall process of building design

The procedure which was followed in this project was recast in the general context of building design and, specially, in relation with the application of modern simulation tools in order to help in the thermal design of a building (André and Lebrun, 2000).

Building design usually involves a number of steps which, when connected together, produce the life cycle of a building : a building is indeed more and more considered as a product which is designed (in several phases), constructed, commissioned, operated and finally renovated or destroyed.

The logical progression of design, the decision-making phases and the information flow are similar in most countries and construction cultures, even though there are differences in the design procedures, professional responsibilities, terminology and the way the construction is carried out. Figure 1 shows a typical model of the design process which identifies the following phases :

- conceptual design
- preliminary design
- detailed design

- construction, commisioning
- facilities management
- renovation

There is of course a need for iteration between these different phases, which means revisions and partial redesign work.

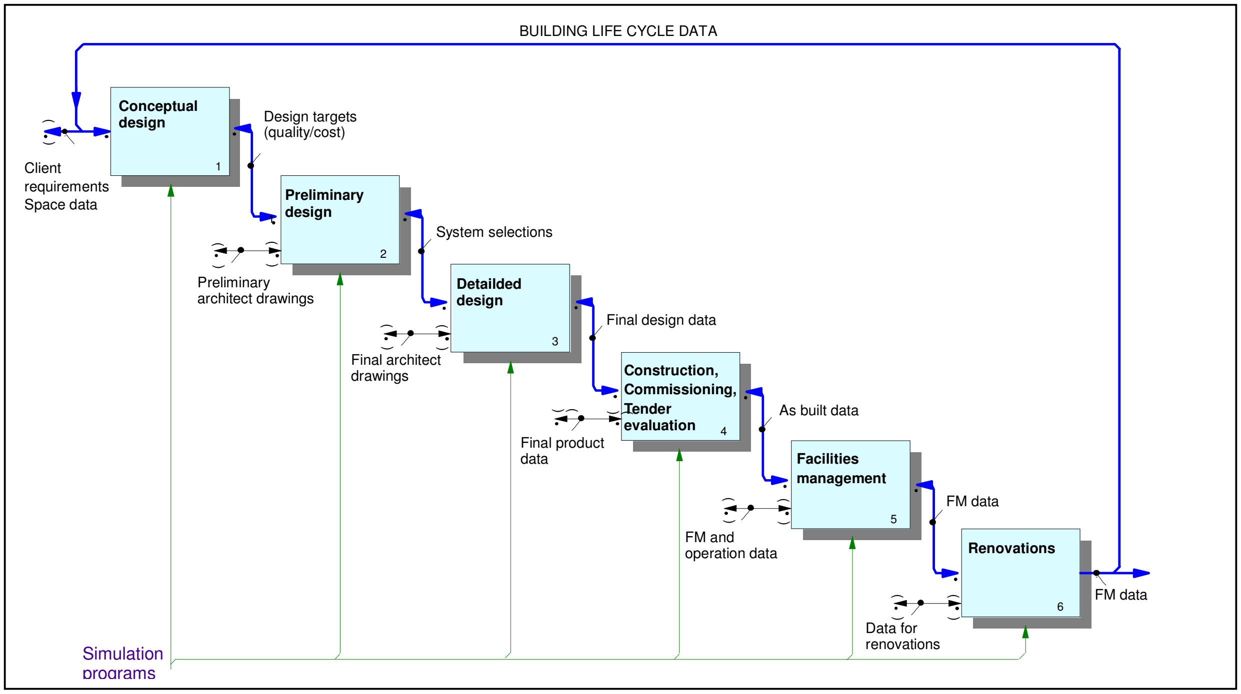


Figure 1 : Typical model of design process (extracted from (André and Lebrun, 2000))

3.1.1. Conceptual design

At this stage, the general context of the building is proposed. The architectural drawings are still schematic and roughly indicate the building envelope, the facades, the orientation of windows, the location of space groups … The HVAC (Heating, Ventilation and Air-Conditioning) designer assists and supports the architect in analysing and comparing alternatives from a technical point of view, with the aims of finding the best overall design option. Important issues at this stage are :

- realisation of the required indoor air conditions
- investment and life cycle costs
- energy consumption
- space requirements for HVAC system

The simulations typically make use of very rough input data and only a limited amount of time can be used for computation and no high demands are set on computational accuracy.

3.1.2. Preliminary design

At this stage, the architect proposes a preliminary design which includes more precise information concerning the building envelope, the facade, the structures, the internal layout. The HVAC designer specifies the technical solutions that fulfill the indoor air quality and cost targets of the project : the HVAC zones are specified, the central plant is dimensioned and the main routes of the ductwork and piping are proposed.

3.1.3. Detailed design

At this stage, the architecture drawings are completed and the bulk of the HVAC design is carried out. The detailed design is traditionally the basis for the call for tenders and the selection of contractors. The HVAC design consists of the following tasks :

- sizing of air handling and cooling equipment
- sizing of piping and ductwork
- selection of room terminal devices
- calibration and balancing of networks
- design of control strategies

3.2. Conceptual design

3.2.1. General considerations

The basic criteria underlying the design process of the reduced scale fog chamber design are related in (André, 2000). They can be summarized as follows :

- budgetary limits and available space on the campus
- simple architecture
- double envelope concept
- "green building"
- security aspects

These criteria led to a building concept characterised by the following characteristics :

- simple volumetric composition (Figure 4) and architectural program (Figure 3) which identifies 4 zones : the fog chamber surrounded by a buffer zone separating the test room from the external environment and two zones placed symetrically on each side of the testing environment (offices and technical area)
- good location of the building on the campus as regards efficient use of natural energy (solar, ambient, ground, …) (Figure 2)
- integration of the building project with other construction projects, either elapsed, on-going or future, in order to reduce costs (Figure 2)
    - construction of an additional parking area on the FUL campus
    - acquisition of a photovoltaic system
    - underground connection to other buildings
- easy (and economic) access to basic infrastructure (Figure 2)
    - water network
    - electricity
    - waste water sewage network

This resulted in the following location on the campus (Figure 2) and in the following sketches (floor plan, Figure 3; external view, Figure 4).

As for most of the building projects, a thermal analysis was not carried out in order to support the conceptual design stage. A number of options were consequently **fixed** before any thermal calculation takes place.

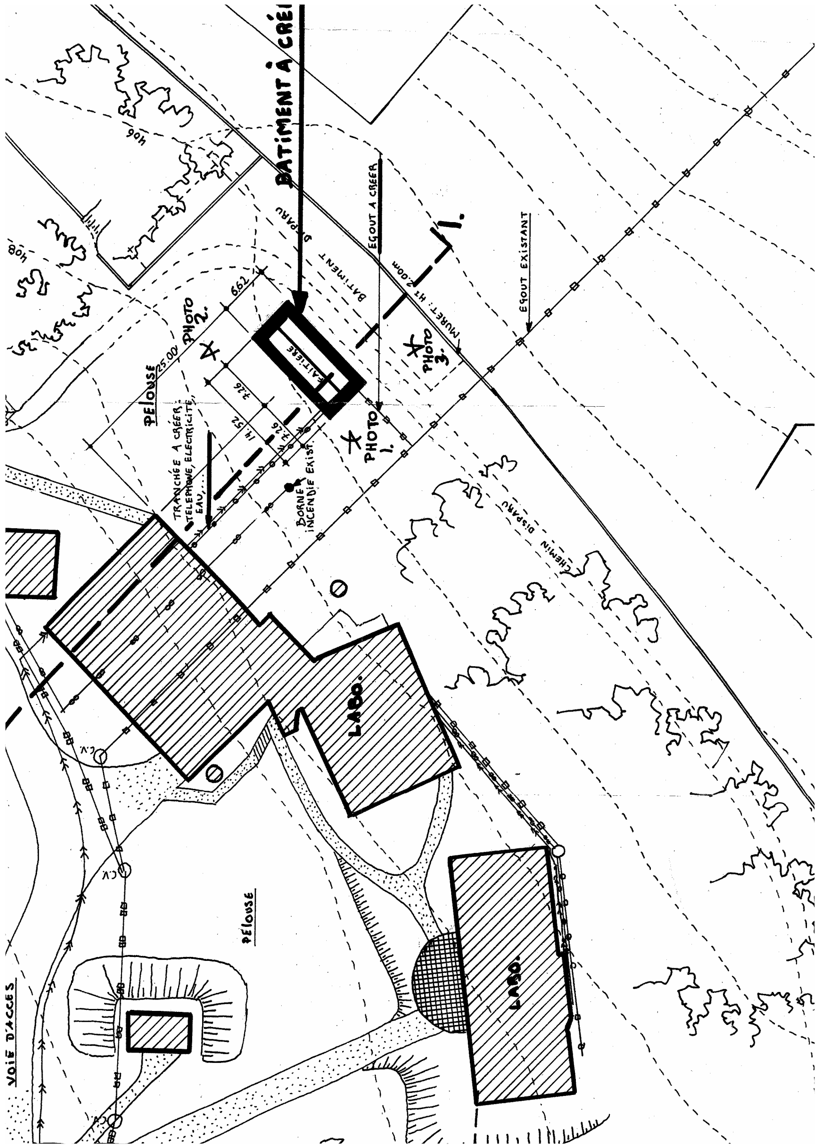


Figure 2 : Selected location of the building on the FUL campus

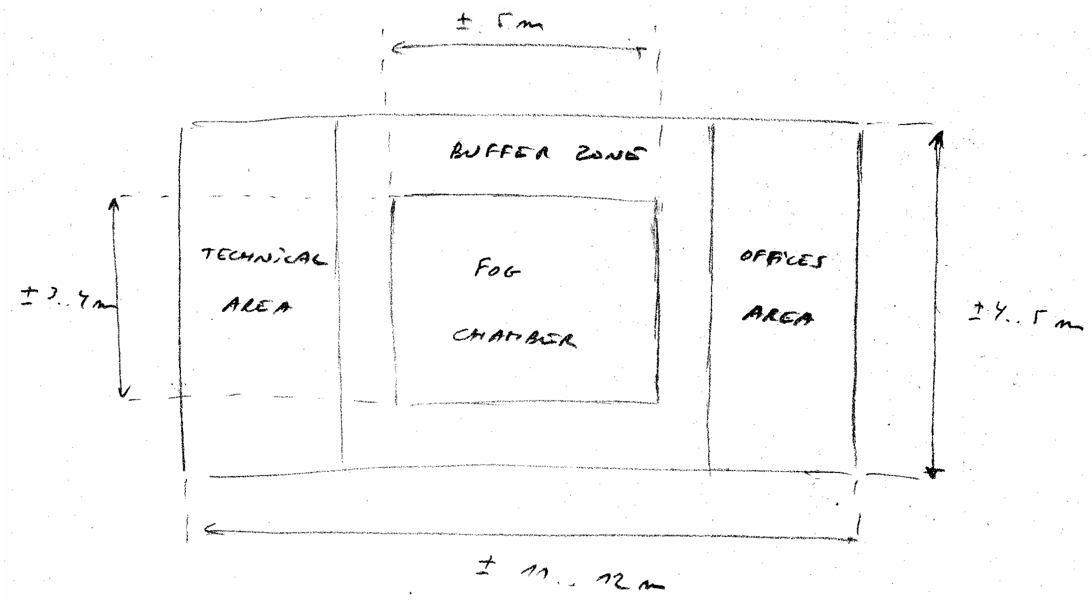


Figure 3 : Schematic view of the conceptual design of the building (floor plan)

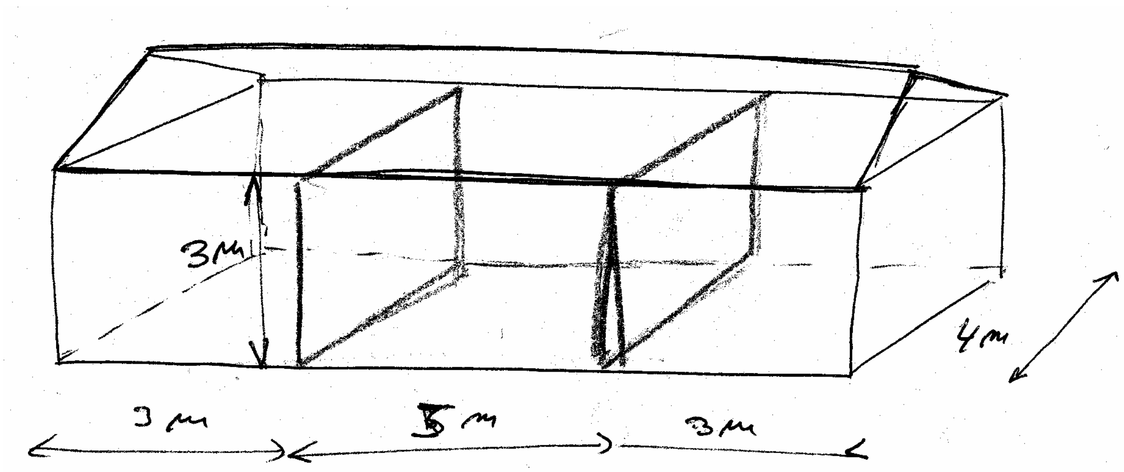


Figure 4 : Schematic view of the conceptual design of the building (external view)

3.3. Preliminary design

3.3.1. Building location

A this stage, the ideas formulated at the conceptual design stage were developed with more details with the use of some calculation mehods.

The location of the building on FUL campus is shown by fig 2, where the already existing buildings and infrastructure are shown as well. The map points out the following features :

- the building is situated at the "back side" of the campus, with respect to the main access roads. The orientation of the building was fixed by the need to integrate the building within the general layout of the campus

- the building appears to be close to the existing networks : water, electricity, sewage. Furthermore, an existing underground tunnel was built when the solar buildings were erected in order to provide an access to a new building which was to be (this building was never constructed) located more or less at the same place as the current project. This makes easier the connection to the electricity network and to the water network

- the building appears to be in good position with respect to the collection of "natural" energy sources : solar and ambient. Figures 8 to Figure 11 show the shadowing effect of the existing solar buildings on the new project at 9 am (solar time) for 4 typical days of the year. This cross-section shows that the existing building does not represent a major obstacle to the solar radiation path towards the new building. Later in the day, the solar building is no longer a mask on the Fog building. Furthermore, the main facade of the building is facing south-east which constitute a good compromise between efficient solar collection and minimization of overheating risk.

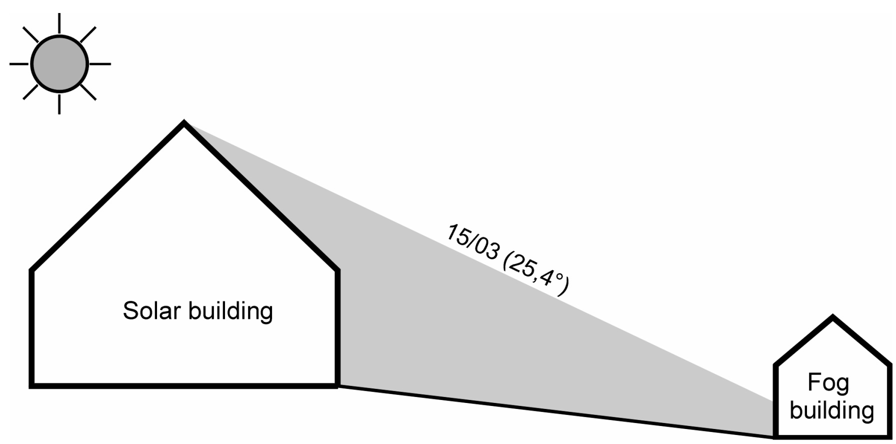


Figure 5 : Shadowing effect of the existing solar buildings on the new building location (15/03)

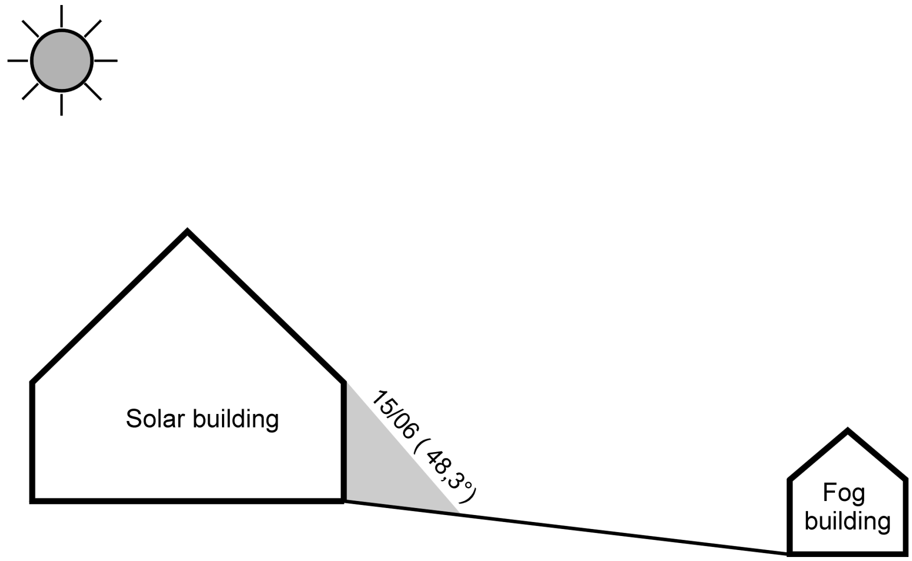


Figure 6 : Shadowing effect of the existing solar buildings on the new building location (15/06)

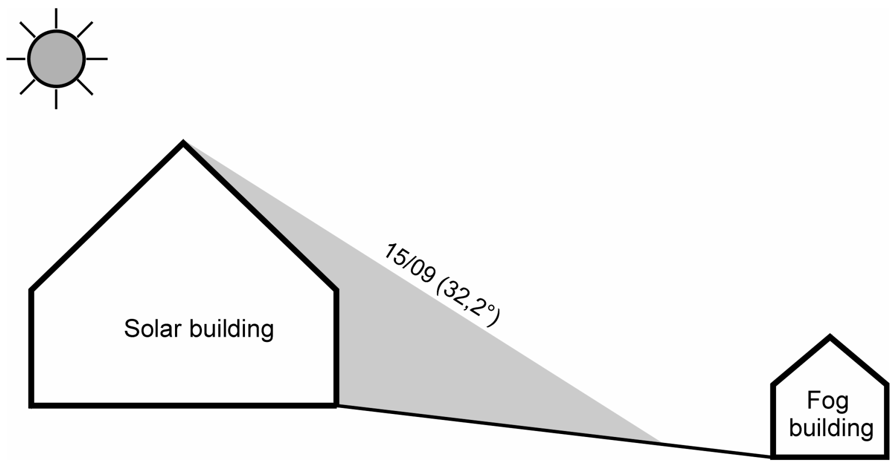


Figure 7 : Shadowing effect of the existing solar buildings on the new building location (15/09)

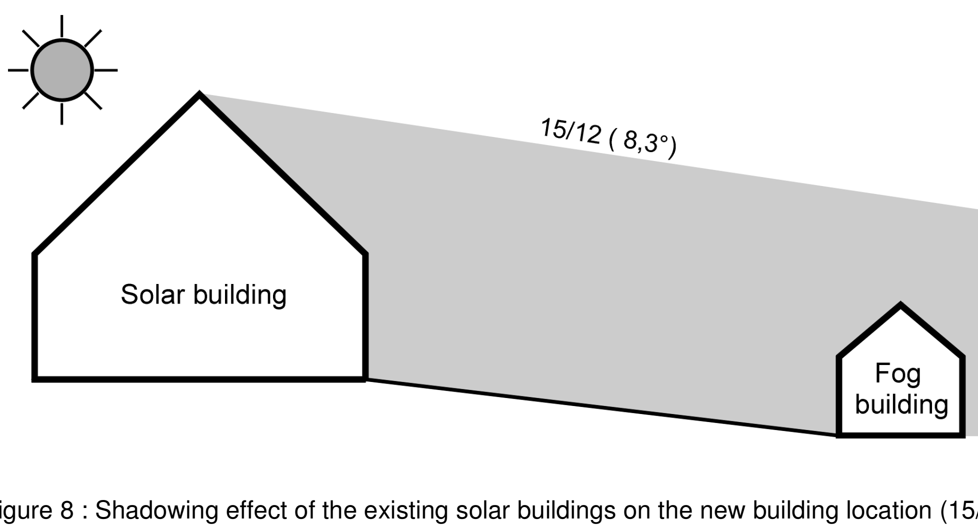


Figure 8 : Shadowing effect of the existing solar buildings on the new building location (15/12)

Furthermore, a double network of burried heat exchangers was installed on the FUL campus, not "too far" from the building project and could be used as both the evaporator / condenser of a reversible heat pump in order to heat / cool the building. A check of the current state of these exchangers had nevertheless to be performed before the final decision to put them again in operation (Figure 9).

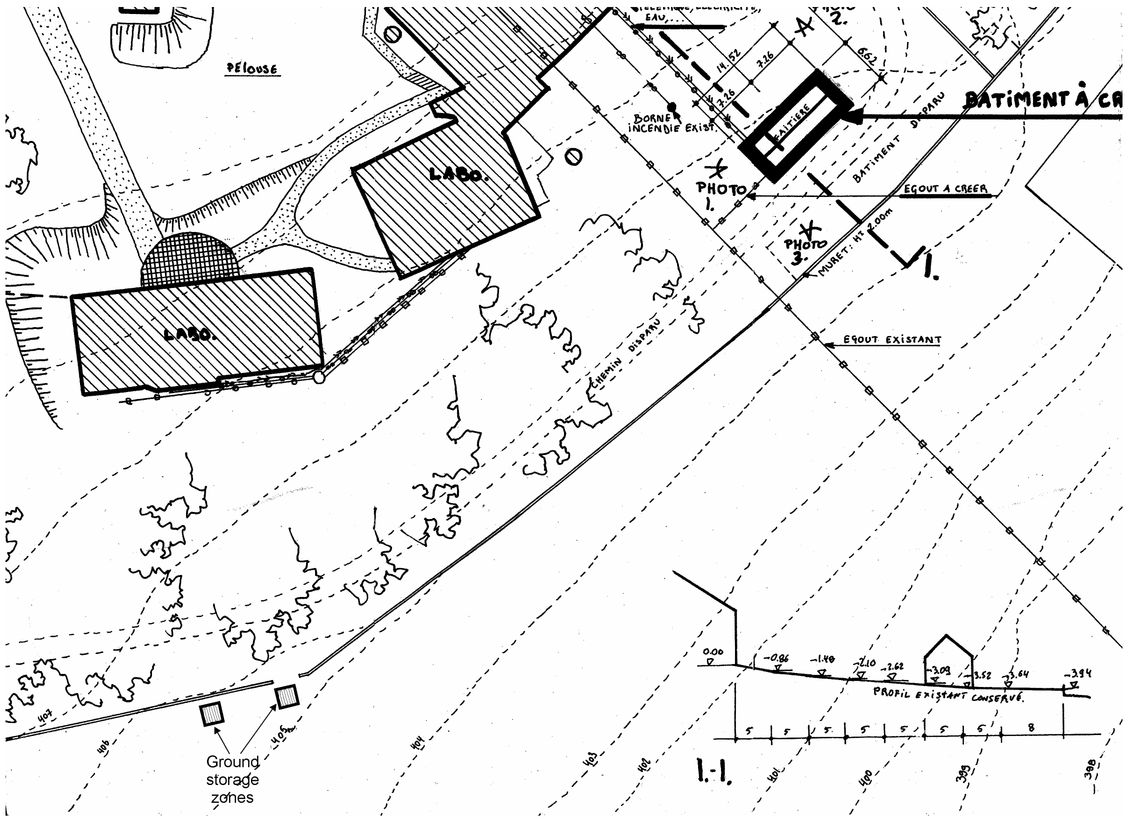


Figure 9 : Location of existing ground storage zones

3.3.2. Building shape and volumetric composition

From the very first (and rough) ideas of the conceptual design shown hereabove, an architect was in charge of proposing a preliminary design.

Due to the specific building functionality and the budgetary constraints, a simple architectural composition was looked for. This resulted in a rectangular shape with a very classical slanted roof design. The overall dimensions of the project were dictated by the zonal functionalities to be provided in the building

The basic idea was to build the climatic room inside a new building using the "double envelope" concept.

Thanks to the double envelope concept, the experimental part of the facility would be made of two separate areas:

- the climatic room (fog chamber)
- the buffer zone

Very roughly, it can be stated that

- inside the climatic room, both the air temperature and the relative humidity would be controlled
- inside the buffer zone, only the air temperature should be controlled

Furthermore, the project should include :

- an "office" area to serve as working place for people during experimentation
- a "service" area where all the equipment (fog production system, HVAC equipment) should be located

The overall dimensions of the building project had to take the following constraints into account :

- budgetary limits
- space an FUL campus
- optimal sizing of the climatic room and necessity to have the additional building space
- time limits

All these constraint ended up with a preliminary project which is represented by Fig. 10 (synthetic architectural image). Fig. 11 (floor plan) identifies the main dimensions of the project :

Climatic room :	Length : 5 m Width : 4 m Height : 3 m Total volume : 60 m^3
Buffer space :	Width ± 1 m all around the climatic room
Office space :	6 x 3 m including toilets and entrance area
Service room :	6 x 3 m

Figure 10: Synthetic image of the building architecture, preliminary design

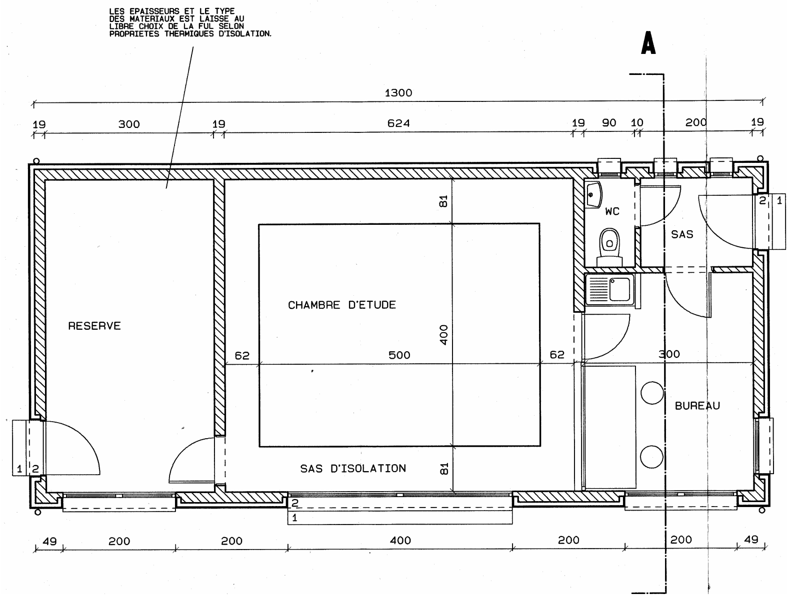


Figure 11 : Floor plan of the first concept of FUL's fog chamber building, preliminary design

3.3.3. Environmental options

The building in which the climatic room was to be placed was constructed on the FUL campus. Because of the environmental conciousness of the Institution, a global approach towards the realisation of a "green" building was pursued which included the following aspects.

- energy options
- selection of materials
- air, water and soil pollution reduction

This resulted in the consideration of the following options.

Energy sources

The following natural and consequently renewable energy sources were considered :

- **solar** (both thermal and photovoltaïc)
- **ambient** sources for reversible heat pumps (for both heating and cooling purposes) : ground (still to be checked at this stage) and air (the simplest method)

Selection of materials

Three basic options were considered for the external envelope of the building

- "classical" envelope : concrete + bricks masonry
- "hybrid" solution : concrete + wooden covering
- "ecological" solution : wooden structure + wooden covering

Air, water and soil pollution

Anoying emissions from the building had to be limited to a minimum.

Air pollution has been limited thanks to the use of "clean" energy sources : solar and heat pumps. The selection of solar sources involved the placement of solar collectors (both thermal and photovoltaïc) on the roof of the building. It was anticipated at this stage that approximatively 15 m^2 of each type of collectors would be installed.

Water emissions had been limited by the connection of the building to a local waste-water treatment plant.

Soil emission : the building was not allowed to generate any residues in the ground.

3.3.4. Preliminary design of the building envelope

The envelope design work was carried out by the architect and was supported by the use of thermal simulation (André, 2001a) in order to compare the three architectural variants concerning the building envelope listed hereabove :

- "classical" envelope : concrete + brick masonry
- "hybrid" envelope : concrete + wooden covering
- "ecological" envelope : wooden structure + wooden covering

The three variants were compared using a detailed thermal simulation program ("TRNSYS").
The main assumptions underlying the application of this program to a fog chamber are given below.

3.3.4.1. TRNSYS simulation program

TRNSYS (Klein et al, 2000) is a modular simulation program devoted to the analysis of energy systems and developed since the early seventies by the Solar Energy Laboratory of the University of Madisson-Wisconsin (USA). The first developments were aimed at the simulation of solar systems and components but, progressively, the tool was generalised in order to adress all aspects of energy in buildings. Therefore, the program offers a library of components (called "Types") that can be connected to each other by means of the simulation description file (called the "Deck").

For this application, the following components were selected and connected together :

- data reader (Type 9) to read meteorological data
- sky temperature (Type 69) to compute the temperature of the sky from ambient temperature and relative humidity
- psychometrics (Type 33)
- solar radiation processor (Type 16)
- forcing function (Type 14)
- building (Type 56)

The building is considered as "multizone" where a "zone" is defined as a spatial entity with homogeneous thermal behaviour (temperature, humidity, …).
The interconnection between the components is shown by Figure 12.

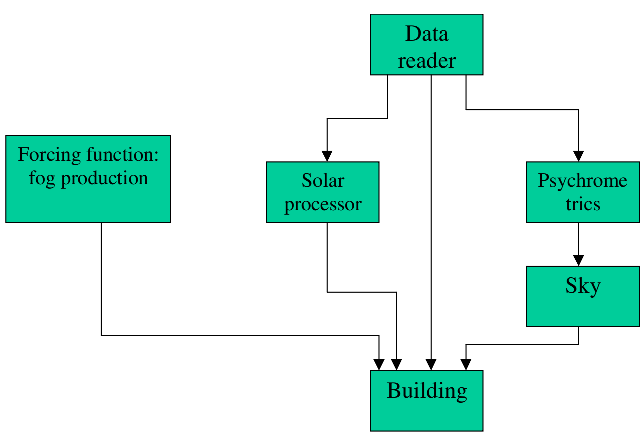


Figure 12 : Information flow diagram for them simulation of the fog chamber

3.3.4.2. Simulation hypotheses

For the simulation of the reduced scale fog chamber, two typical meteorological periods were considered

- a winter period (January month)
- a summer period (August month)

For each period, a standardized "numerical experiment" was defined, made of 2 weeks with the following distribution :

- a "numerical" pre-conditioning period of 10 days
- an "experimentation" period of 2 days : this includes climate control and, eventually, fog production
- a relaxation period of two days.

The main component of the simulation is of course the building which is modeled by Type 56. This model is able to calculate, for a building divided into an arbitrary number of zones, the evolution of both the temperature and the psychrometric variables in each zone. Therefore, the following information has to be provided to the model :

- the zoning strategy; 4 zones were defined : test room, buffer zone, office and technical area and the walls composition
- the construction materials
- the infiltration rate in each zone
- the ventilation rate (with the associated temperature and relative humidity) in each zone
- the heating and cooling power injected in each zone (associated to an "idealized" control)
- the internal gain, expressed in terms of thermal power (both convective and radiative) and moisture (water vapour).

In this application, the transfer of moisture through the walls was not taken into account because of the relatively long time constant associated to these physical processes.

3.3.4.3. Control conditions

As only the thermal behaviour of the building envelope was of interest here, a very simple control strategy was elaborated, defined as such : during the experimentation period, the temperature in the buffer zone is maintained to 10°C. The objective of the simulation was to calculate the time required to bring the buffer zone to this temperature.

3.3.4.4. Results

Table 1 shows the time required to reach the prescribed conditions in the buffer zone in function of the type of construction and period of the year.

	Winter	Summer
Wooden construction	22 h	22 h
Hybrid construction	28 h	28 h
Classical construction	28 h	28 h

Table 1: Thermal pre-conditioning period of the reduced scale fog chamber

The table clearly shows that the constitution of the external envelope has not a strong influence on the pre-conditioning time of the fog chamber. The "all-wood" construction offers less thermal inertia and consequently allows a quicker preparation of the test room.

The thermal calculation also allowed to calculate the heating energy consumption required to maintain the bulding in the usual comfort conditions. Results are given by table 2:

Variant	Heating energy consumption (kWh)
Wooden construction	3390
Hybrid construction	5060
Classical construction	5260

Table 2 : Heating energy consupmption of the reduced scale fog chamber building

As a result of this design phase, the “all-wood” construction was definitely selected for the building

3.4. Detailed design of the building

3.4.1. Building envelope and structure

3.4.1.1. General characteristics of the envelope

In order to meet the environmental criteria mentioned here above, it was decided to select a wooden structure and envelope. The preliminary thermal calculation presented hereabove revealed that this was not a major obstacle to the efficient control of an adequate indoor climate (André, 2001a).

Along with discussion with the FUL staff, the architect developed the final design of the building. The main changes compared to the preliminary design included a slight increase of the floor plan dimensions and the provision of an additional space (a meeting-room) above the offices. As mentioned here above, the main facade of the building is facing south -east. Because of the "secondary" objective to make the building appropriate for thermal experimentation, this facade was given a relatively high fenestration ratio. Furthermore, this facade was seen as the main access to the climatic room, especially in order to introduce big objects in this room. Therefore, the facade was equipped with a large (glazed) double sliding door. The program of the building identifies two specific zones on each side of the climatic room : one zone for the office and one zone for the technical area. The office part was located on the north-east facade, in order to reduce the overheating risk in the occupied part of the building. This facade was equipped with two windows in order to give enough day lighting (diffuse light) in the office. On the south-east facade, the office receives two additional windows (one in the roof), which still increase daylighting without involving too much solar gains. On the opposite, the south-west facade is totally opaque to reduce solar gains. The technical area is equipped with a window in the south-east facade to provide some daylighting. The northern facade is almost totally opaque as well with only a small window in the toilets zone. To summarize, Figure 13 to Figure 16 show a view of the different facades of the building :

- South-east facade (Figure 13) : main facade with a high fenestration ratio
- North-east facade (Figure 14) : facade giving access to the occupied part of the building
- South-west facade (Figure 15) : critical facade as regards solar gains, therefore totally opaque
- North-west facade (Figure 16) : totally opaque

Furthermore, Figure 13 shows the location of the solar collectors (see below). Two types of solar collectors were to be installed :

- thermal collectors
- photovoltaic collectors (in the context of a demonstration project funded by the main belgian electricity distributor in which FUL was anyway participating)

For several reasons (architectural integration, size of the modules, easy connection between the thermal collector and the technical area), it was decided to locate the thermal collectors above the technical area while the photovoltaic panels were placed in the central part of the building, above the main entrance door.

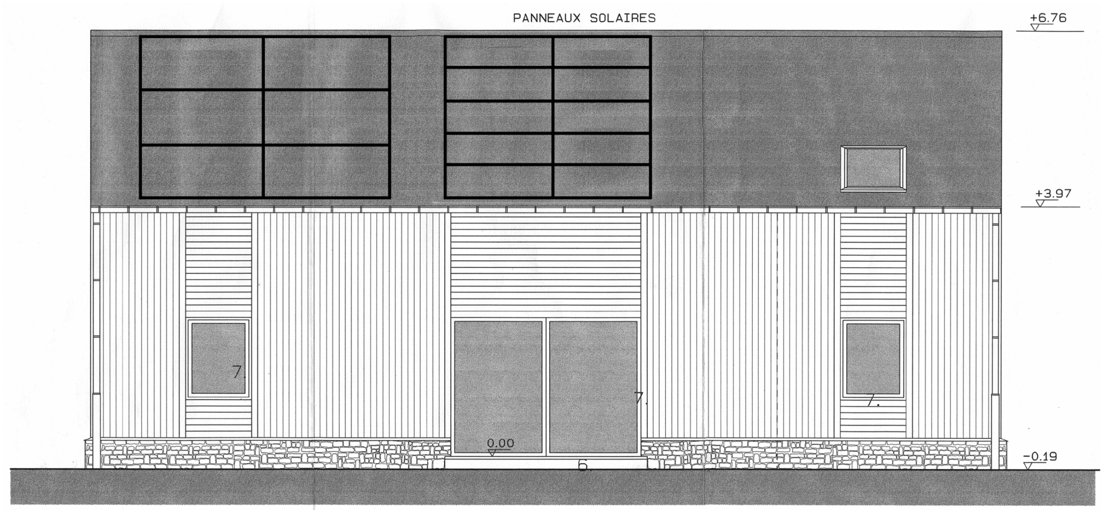


Figure 13 : View of the south-east facade

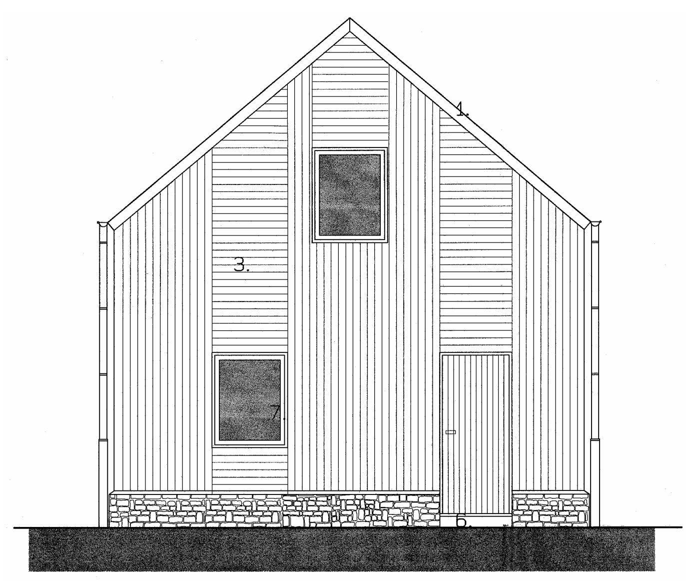


Figure 14 : View of the north-east facade

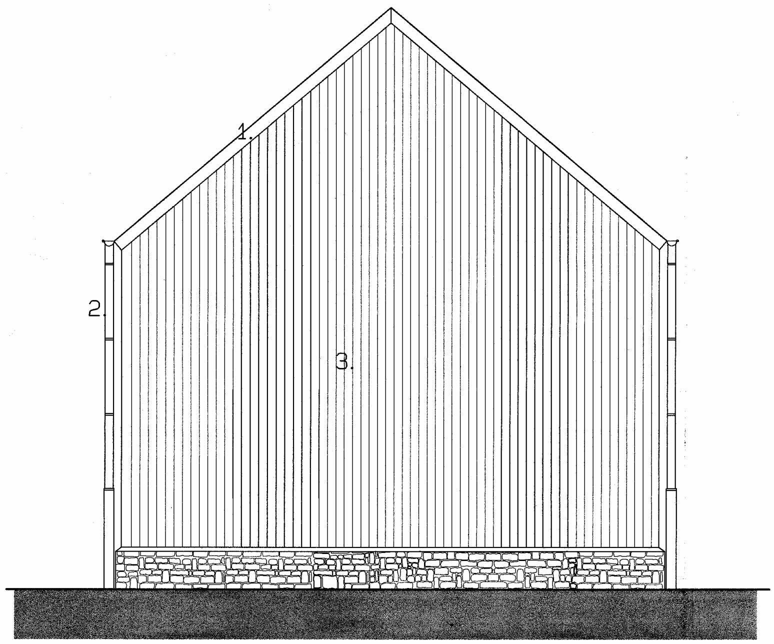


Figure 15 : View of the south-west facade

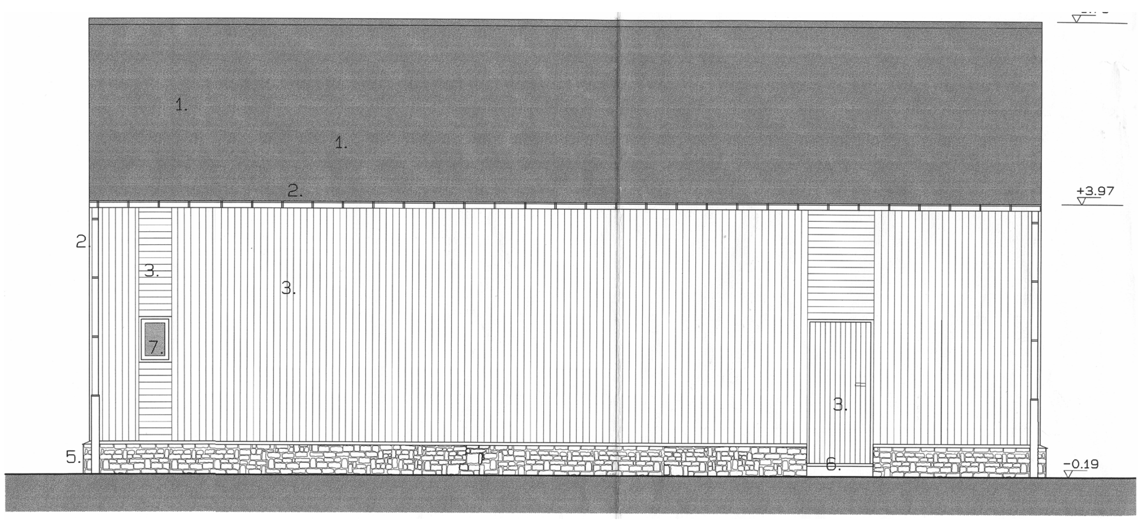


Figure 16 : View of the north-west facade

All facades would be covered with wood. The roof would be covered with tiles. It was anticipated (because, at this stage the HVAC design is not complete) that the evaporator of the heat pump (when working in the "heating mode") would be placed on the south west facade, which appears as the most efficient in winter time.

3.4.1.2. Building structure

Because of the decision to provide an additional space above the offices area, the overall height of the building was slightly increased. The space organisation of the offices was changed accordingly (need to have a staircase and change of the location of the toilets). The updated floor plan which results from this modification is given by figure 17. The corresponding cross-section is given by fig. 18. Compared to that design, an additional change (not represented on the picture) was brought afterwards by removing the crawl space and making the slab-on-grade.

Due to the relatively small size and limited loads of the building, the structure is made of bearing walls. The roof was designed as supported by wooden beams (15 m long) supported by the external walls and the two intermediate walls separating the buffer zone from respectively the office room and the technical area. Consequently, those walls were sized as load - bearing as well. The structure of the load-bearing walls is made of 14 cm thick trusses, placed each 40 cm and reinforced by wooden panels (12 mm thick) on each side. In addition, the vertical trusses are chained to each other by horizontal trusses. The wooden panels are made of "OSB" ("Oriented Strand Board") panels. Additional elements are reinforcing the windows and doors passages. The non-bearing internal walls are of the same composition but the thickness is limited to 9 cm. Figure 17 shows the floor plan of the building, with identification of the load-bearing walls while Figure 21 shows a cross section in the office area.

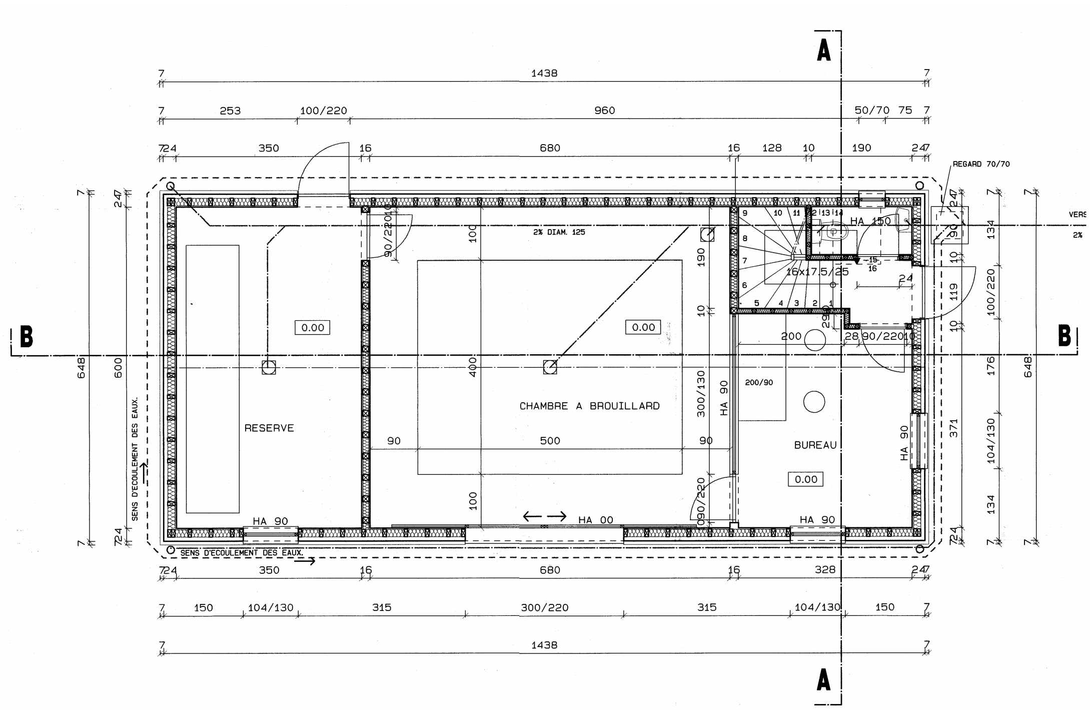


Figure 17 : Floor plan of the building, final version

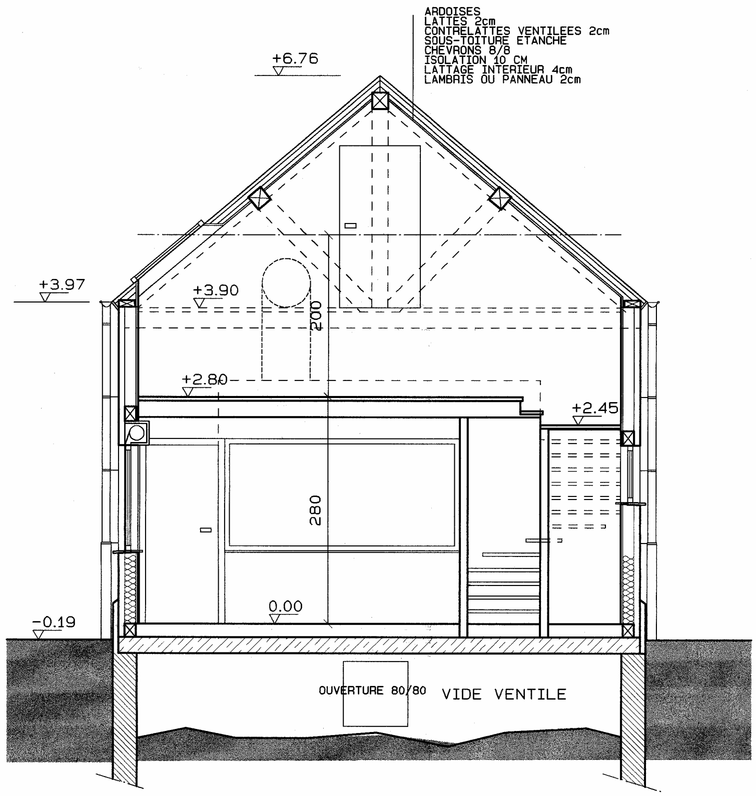


Figure 18 : Cross-section of the building in the offices area
(the crawl space was removed in the final design)

3.4.1.3. Walls composition

The composition of the different walls of the building is as follows.

External walls (Figure 19)

From outside to inside

- wooden covering : 2 cm
- ventilated air-gap : 2 cm
- wooden panel ("OSB") : 2 cm
- wooden structure including rock wool : 14 cm
- vapor bareer
- wooden panel ("OSB") : 2 cm

Windows

A number of windows are located in the outside walls.
Their characteristics are :

- wooden frame ("meranti"), thickness : 0.056 m
- double low-e glazing with the following thermal and optical properties
  - U_{value} = 1.1 W/km^2
  - solar transmittance : 0.6
  - solar absorption : 0.1
  - solar reflection : 0.3

Doors

The external doors are as follows.

- office door : wooden construction + partial glass covering
- technical room door : totally wooden construction
- south facade door : sliding "door - windows"

All windows (including the sliding door-window) are equipped with external shutters (also made of wood) in order to create “dark” conditions when required.

Roof

In order to meet the environmental criteria as regards energy sources, a part of the roof was covered with solar collectors. Two types of solar collectors were selected :

- photovoltaïc (PV) panels; area : 10.5 m^2
- thermal collectors; area : 14.4 m^2

Under the solar collectors (both thermal and PV), an insulation layer (thickness : 0.15 m) takes place. The part of the roof which is not covered by either type of solar collectors is made of the following composition(F   Figure 23)

From outside to inside :

- tiles
- ventilated air-gap
- wooden structure including thermal insulation (rock wool); thickness : 0.15 m
- vapour barren
- wooden panels

Finally, the roof is equipped with one roof window located above the offices area. The thermal and optical properties of this windows are as follows.

- U_{valve} : 1.1 W/tr m^2
- Solar Transmittance : 0.6
- Solar Absorption : 0.1
- Solar Reflection : 0.3

Internal partitions (Figure 21)

Two types of internal partitions are present in the building.

- Two vertical load-bearing walls are separating the buffer zone and the attic from, respectively, the technical room and the office. These partitions have the same composition as the external walls, the final covering excepted, ie
  - wooden panel (OSB)
  - wooden structure including rock wall panel, 14 cm thick
  - wooden panel (OSB)

The thickness of the panel is 18 mm for those facing the technical room and 12 mm for all other panels. Furthermore, the wall separating the office from the buffer zone is equipped with an internal window (2 x 1.15). The thermal and optical properties of this window are :

- U_{value} : 3 W/m2 K
- Solar transmittance : 0.7
- Solar absorptance : 0.1
- Solar reflectance : 0.2

The walls separating the buffer zone from the office and from the service room are both including a wooden door (0.9 x 2.05).

- The internal partitions within the office zone are non-bearing and have the following composition :
  - wooden panel, thickness 12 mm
  - wooden structure including rock wool panels, thickness 89 mm (wooden pieces, 89 mm thick, placed every 40 cm and separated by rock woo panels)
  - wooden panel, thickness 12 mm

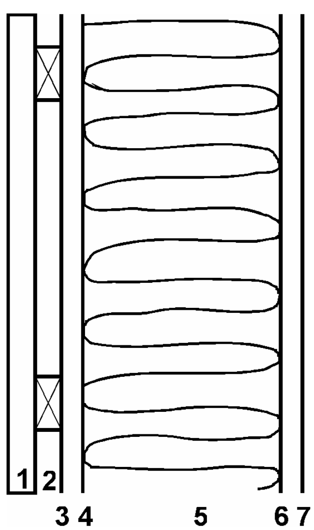
These partitions include internal doors (identical to those mentioned here above), where appropriate.

Floors

- At ground floor, the building is built on a "slab - on - grade" (14 cm thick). In all the zones but the technical area, the concrete slab is receiving a floor heating/cooling system embedded in a mortar slab. Therefore, an insulation layer (8 cm thick) takes place between the slab and the floor heating cooling system(Figure 25). The final covering of the floor is made of pavments. In the technical area, the concrete slab receives a thinner layer of thermal insulation (3 cm) and a mortar slab without any covering.

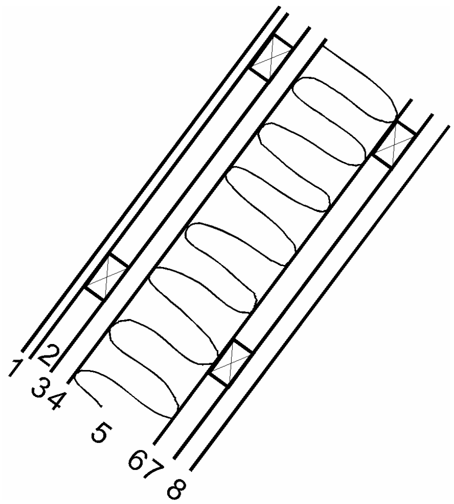
- The floor between the ground level and the first level is made of wooden beams, placed approximatively every 40 cm, and supporting wooden panels ("OSB", as for the walls). An insulation layer (15 cm) takes place between the wooden beams (Figure 26)

Figure 19→F Figure 23: Summarize the composition of the different-walls



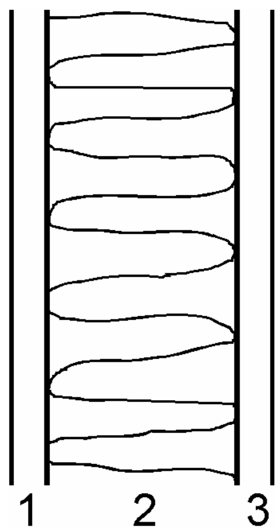
1. wooden covering ("Douglas") (20 mm)
2. ventilated supporting trusses (20 mm)
3. rain protection
4. OSB panel (12 mm)
5. rock wool (140 mm) + wood trusses
6. vapour bareer
7. OSB panel (12 or 18 mm)

Figure 19: External wall



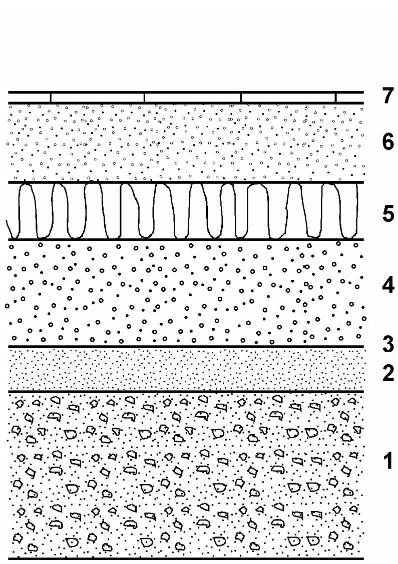
1. tiles (10 or 20 mm)
2. ventilated trusses
3. trusses
4. under roof
5. rock wool (between wood trusses)
6. vapour bareer
7. supporting trusses
8. OSB panel (12 mm)

Figure 20 : Roof



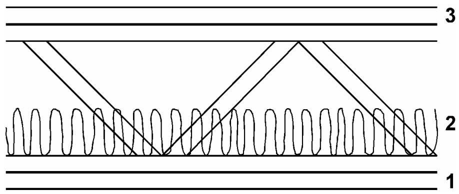
1. OSB panel (12 or 18 mm)
2. rock wool
   - bearing walls : 140 mm
   - non bearing walls :89 mm
3. OSB panel (12 mm)

Figure 21 : Internal partition



1. stone (200 mm)
2. sand (50 mm)
3. water bareer
4. reinforced concrete (140 mm)
5. extruded polystyrene (80 mm)
6. mortar slab (including heating / cooling pipes) (100 mm)
7. floor covering

Figure 22 : Floor heating slab



1. OSB panel : 12 mm
2. wooden beams (350 mm), including rock wool (150 mm)
3. OSB panel : 12 mm

Figure 23 : Intermediate floor

3.4.2. Design of the control strategies

A thermal analysis based upon simulation was carried out to develop a first approach of the design of the control strategies. The main objective here was to verify that the simulation tool was able to perform a comparative analysis of different control strategies of the test room.
On an intuitive basis, the creation of adequate control conditions in the test room can be achieved through several possibilities : thermodynamical or mechanistic production; control of the test room or of the buffer space; combination of these actions.
For instance, the following actions can be carried out :

- Thermodynamical production
    - test room control
        - control of the room temperature to the dew point
        - control of the relative humidity to the saturation state
    - buffer space control
        - control of the buffer space temperature to the dew point
- Mechanistic production
    - control of the test room relative humidity to the saturated state by injection of liquid water
- Combination of actions
  For instance, a possible strategy would consist in carrying out a mechanistic fog production without climate control followed by the begin of climate control just after the end of fog production

3.4.2.1. Evaluation criteria

When comparing, using a simulation tool, different control strategies, it is of course necessary to have clearly defined evaluation criteria in mind. The simulation tools as those used in this analysis (TRNSYS and ESP-r (Clarke, 2001)) were primarily developed for the purpose of energy conservation in buildings. When such a goal is attempted for, the evaluation criteria are obvious :

- minimization of energy consumption over a given period, and, at the same time
- maximization of thermal comport in the building

When the production of artificial fog is looked for, the definition of the evaluation criteria is obviously different. It appears also as very difficult to write down. Here is a short list of possible criteria.

- duration of the thermodynamical pre-conditioning period
- quality of the control during the period where climate control in action
- time variation of the heating and cooling signals as an indication of the wear of the control actuators
- energy expenditure

3.4.2.2. Results from TRNSYS simulations

The TRNSYS simulation environment defined hereabove was enhanced to adress control simulation. A number of components were added, resulting in the scheme given by figure 24.

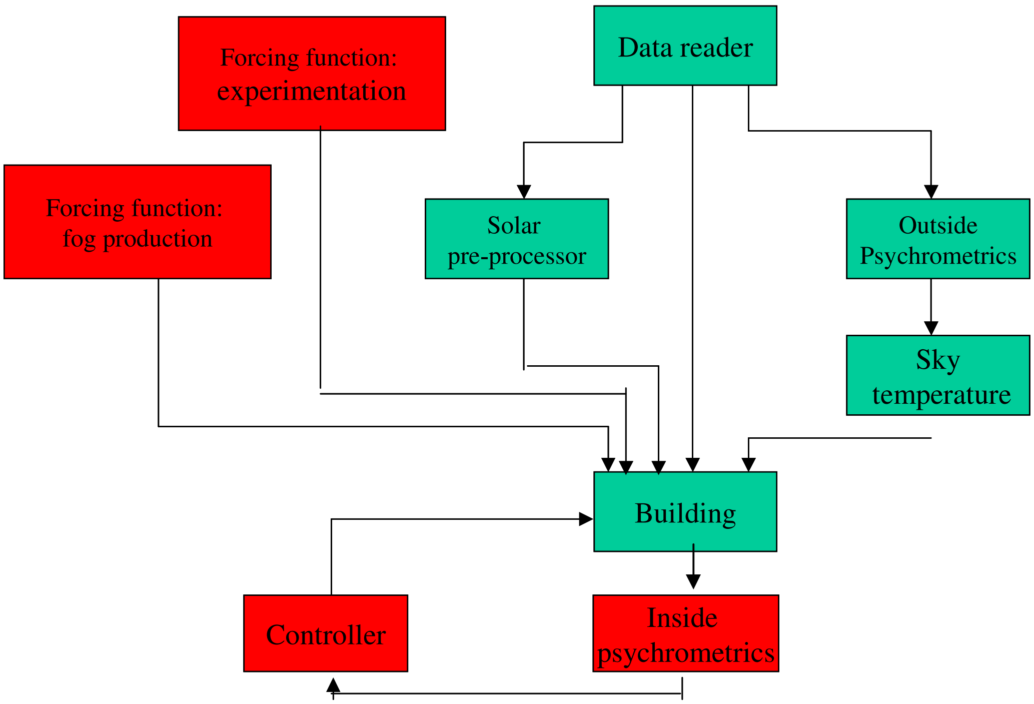


Figure 24 : Simulation environment for control simulations.

Not all the different possible control strategies were tested (in simulation) at this stage, one of the reasons being the lack of evaluation criteria. Nevertheless, testing of an exemplary control strategy revealed an interesting feature.
Figure 25 shows an experiment where climate control was started after 240 h. The temperature of the test-room was forced to the dew point (which depends on the air temperature). The required action was obviously a cooling action but this action, not only made the controlled variable (test-room temperature) close to the set point but, at the same time, decreased the set point, asking for an additional cooling power. This resulted in a cumulative sequence bringing the test room temperature down to 5°C (where the maximum cooling power was obtained). This shows that the selection of the dew point temperature might not be the most adequate control strategy.

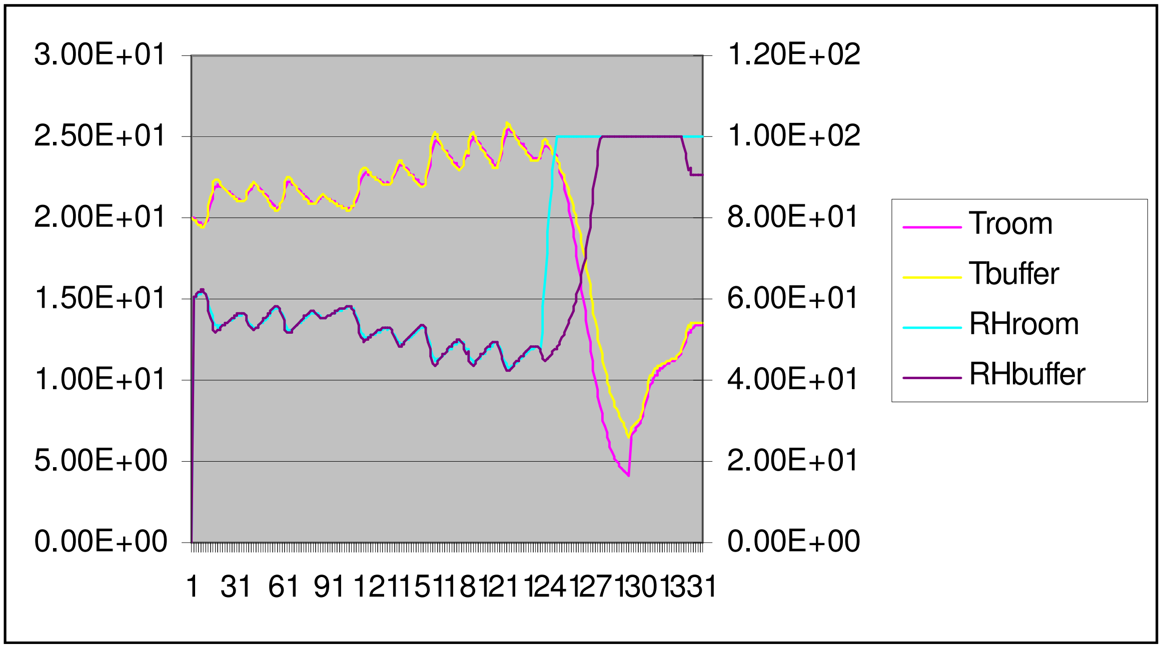


Figure 25 : Experiment with the dew point temperature as the control variable.
Cumulative cooling effect

3.4.2.3. Results from ESP-r simulations

ESP-r simulations were conducted by partner UStrath and the main results are given in (Kelly, 2001a) and (Kelly, 2001b). The overall conclusions of this complementary approach are as follows. More details are given in the WP2 report.

Several options for control of conditions within the test chamber were examined which fall in two categories: direct control and indirect control.

Direct control entails performing psychrometric operations on the air within the test chamber, for example heating and humidification, through connection of HVAC equipment to the test room.

Indirect control entails controlling the psychrometric state of the air through the manipulation of temperatures in adjacent spaces (the buffer zone) or surfaces (underfloor heating)

- direct control methods proved the most suitable at maintaining close control of environmental conditions within the test chamber
- direct control of temperature and relative humidity provided stable conditions at low energy expense and plant capacity
- cooling of the air inside the space to its dew point temperature also provided relatively stable conditions, however the dew point temperature obtained varied between each operation of the control algorithm; this would cause problems with repeatability of experiments
- the cooling load and energy consumption associated with the dew point controller was high in these simulations
- underfloor heating and cooling proved highly unsuitable for tight control of air temperature, in addition plant loading was significantly higher than that required for direct control methods
- indirect control of the temperature in the test chamber proved equally successfull, with poor control of conditions, high plant loading and high expenditure of energy
- it was noted that the performance of the dew point control method was very sensitive to the moisture content in the test chamber

- additional simulations were run, using an ESP-r augmented model with a wetted surface model, increasing the humidity in the test chamber, plant loadings and energy consumption associated with the dew point controller were drastically reduced
- more simulations were run with a more realistic PID control of temperature and relative humidity in the test chamber. These simulations indicated a slight deterioration in the performance of direct control, with initial fluctuations in temperature and increased plant loading and energy consumption
- attempts were made to improve the performance of the indirect controller, through a change of control strategy and use of PID control, however the performance remained unsatisfactory
- overall direct control of temperature and relative humidity within the test chamber looks the most promising means of achieving stable conditions
- Additional simulations revealed that, at high levels of internal gains (500W), the HVAC system struggles to maintain the set point temperature in both summer and winter, with temperatures rising 1-2°C above the set point
- The CFD simulations reveal that modulating the supply air temperature creates inhomogeneity in the test room temperature with temperatures varying up to 2.5 °C
- To alleviate the problem of temperature inhomogeneity a different control strategy was used inside the test room where, after a period of pre-conditioning, the supply air temperature was held to the set point temperature. The floor cooling/heating system was also used to precondition the space up to 4 hours prior to the test.

As a conclusion of this simulation work, the following control strategy was suggested :

- 4 hour pre-heating or pre-cooling of the floor
- 2 hour pre-conditioning of the buffer space
- 2 hour pre-conditioning of the test chamber to bring temperature up to the setpoint and the relative humidity close to 100%
- during the test supply air and surface temperatures should be maintained at the set point temperatures, however this requires that internal gains are kept an absolute minimum

4. Design of the HVAC system

4.1. General context of the HVAC system design

The HVAC design was based upon the preliminary thermal analysis (André, 2001a) which, although carried out on the data of the preliminary design, was checked and further detailed later (André, 2001b). As a recall, the general context of the design was including :

- the energy sources
  As much as possible, the energy sources would be "extracted" in the local environment. Two sources would be used :

  - solar energy
  - ambient energy

  The latter would be converted into useful heating or cooling using a (reversible) heat pump (see below) and the conversion technique will make use of electricity. As a consequence of this choice, no CO_2 associated with energy **consumption** would be produced in-situ.

- the energy conversion techniques

    - **Solar energy** would be converted into heat (thermal collectors) and electricity (photovoltaïc panels).
      Solar heat would be either stored in a hot water tank or directly distributed through a heating floor. Solar electricity would be directly consumed in the building.

    - **Ambient energy** would be converted into heat or cool by means of a reversible heat pump, using some electricity. The reversibility of the heat pump allows to use it to either heat or cool the building. It is also possible to heat some part of the building while cooling some other part. For instance, in order to conduct fog experimentation in mid-season it might be necessary to cool the fog chamber and, at the some time, to heat the office. In order to allow the maximum flexibility, it is anticipated that the reversible heat pump will work between two buffer storages : one with warm water, the other with cold water. It would be possible to hydraulically connect either storage tank to one given heating/cooling emitter in the building or external heat exchanger. The use of an existing ground heat exchanger (fig. 12) as evaporator/condenser of the heat pump was definitely left out for economical reasons.

- the terminal devices

  Heat and cool would be distributed in the building by means of two types of emitters :

    - radiative emitters :floor and ceiling
    - convective emitters : ventilation system

Not all zones would be equipped with all terminal devices. **Erreur ! Source du renvoi introuvable.** gives for each zone the type of emitter which would be connected.

Zone	Floor heating	Floor cooling	Cooling ceiling	Ventilation
Chamber	X	X	X	X
Buffer	X	X	-	X
Office	X	X	-	-
Technical	-	-	-	-
Attic	-	-	-	-

Table 3 : Active terminal devices for each zone

X : installed
\- : not installed

The floor heating / cooling system would be made of polyethylene pipes embedded within the mortar of the slab. In order to provide the maximum flexibility, three independent loops would be created :

- test room
- buffer space
- office

It was anticipated at this stage that the heating/cooling ceiling would be made of aluminium panels including copper pipes. The panels, only located in the test room, would be perforated in order to allow ventilation to take place in the room through this (false) ceiling.

The ventilation system (at this stage of the project, see below for evolution) would be a "classical" air handling unit, working probably without recirculation and made of the following components :

- filter
- heating coil
- cooling coil
- humidifier
- fan

The air handling unit was sized for 1000 m^3/h and the heating/cooling coils would be connected to the heat and cold storage associated with the heat pump.

4.2. Possible HVAC schemes

Based upon these specifications, a number of schemes were proposed, with an increasing order of complexity (André, 2001c).

Starting from the general concept presented hereabove, the following system was proposed, as a first sketch :

The proposed system is made of the following components (Figure 26) :

- a reversible heat pump connected to the terminal device through a heat exchanger
- a solar thermal system connected to a storage tank and to the terminal device through another heat exchanger
- the terminal devices :
  - radiating floor
  - radiating ceiling
  - air handling unit

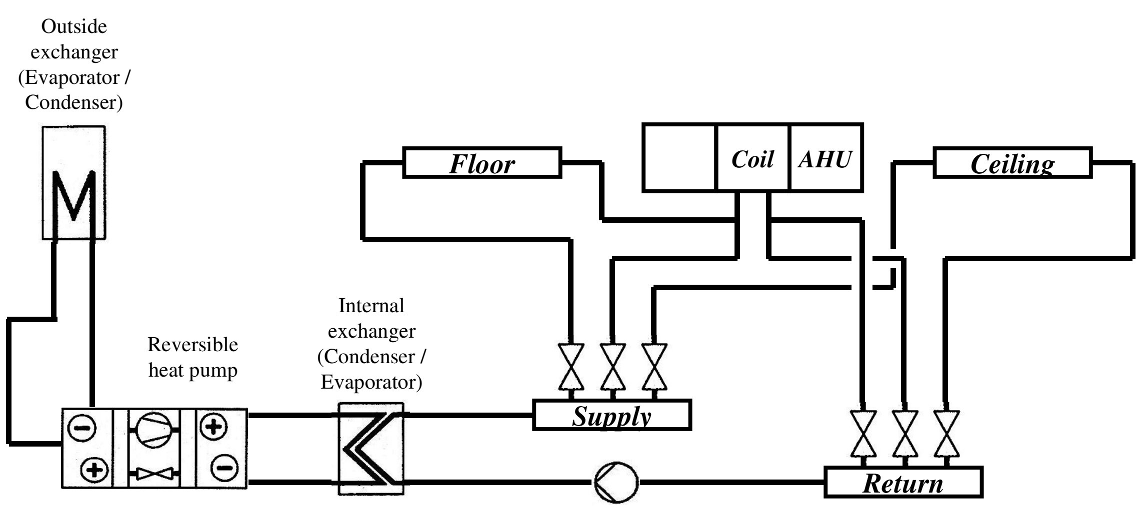


Figure 26 : Basic scheme for the HVAC system

This schema was certainly not complete yet and a number of questions remained at this stage unsolved :

A. Was it necessary to simultaneously provide heating and cooling to the building ?
It is likely that, during the operation of the building, some rooms will require heating (eg the office in wintertime) while others will require cooling (the fog chamber). If this is to be realized simultaneously, the schema proposed by Figure 26 is no longer valid and more complex solutions can be derived :

- to connect each terminal to either side of the reversible heat pump (Figure 27). This obviously bring a number of hydraulic complexities in the network. Management of the reversibility of the heat pump becomes very difficult

- to operate the heat pump between two storage tanks (one for hot water, one for cold water) and to hydraulically connect each terminal device to each relevant storage tank (28). The same hydraulic complexity as above appears while the operation of the heat pump between two fixed temperature set points is very problematic

- to forget the use of a reversible heatpump and to use simultaneously two machines : one for healing, one for cooling (Figure 29). Each machine is connected to a storage tank (if required) and each tank is connected to the relevant terminal device. This solution is hydraulically simpler, but obviously requires more investment.

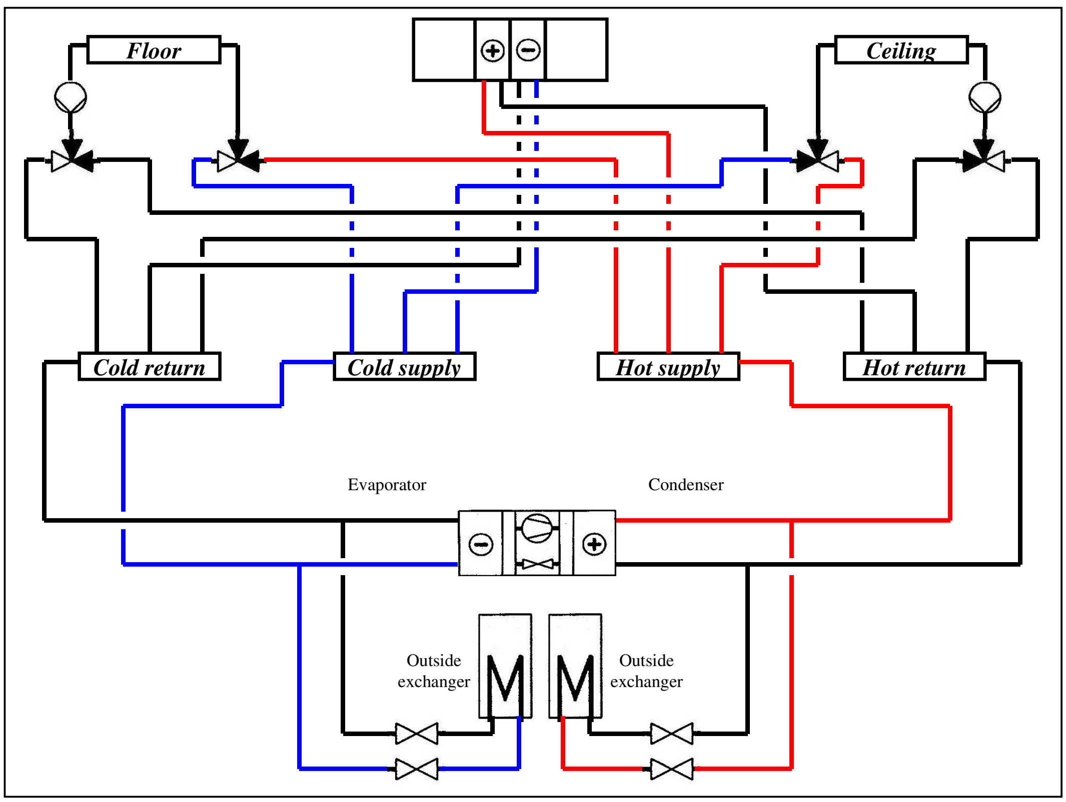


Figure 27 : HVAC schema with one reversible heatpump and no storage

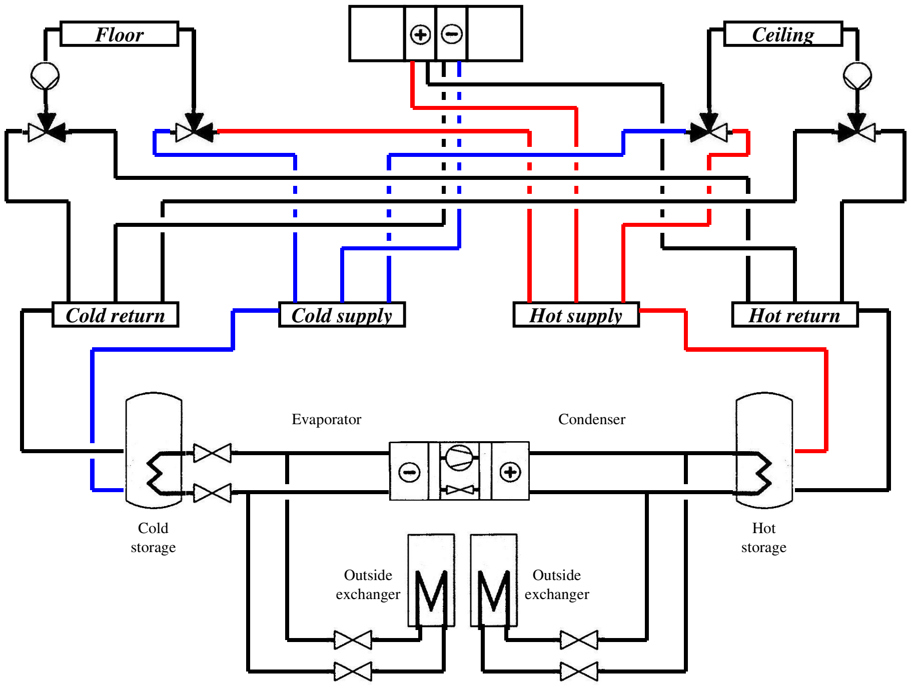


Figure 28 : HVAC schema with one reversible heat pump and two storage tanks

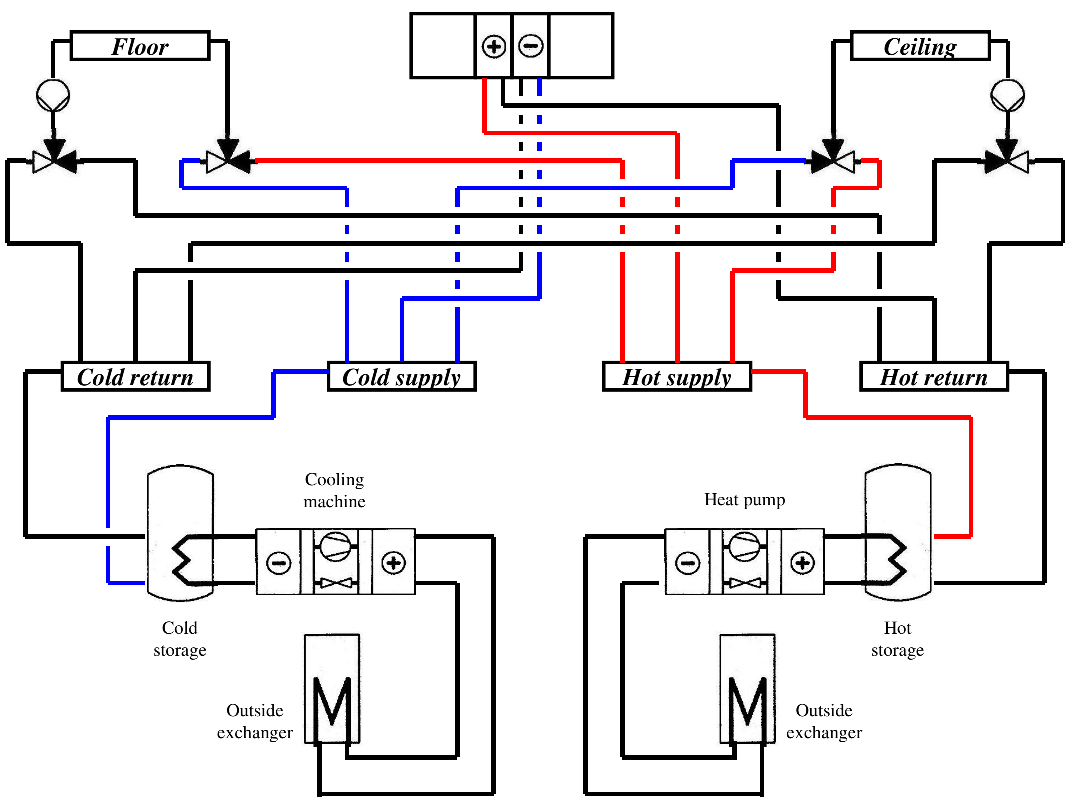


Figure 29 : HVAC schema with two heatpumps and two storage tanks

B. Use of heat and cool storage
This question is answered above. An additional question concerns the way the solar thermal plant is connected to the rest of the system. This probably requires an additional storage tank (for hot water) which is used to :
- absorb the excess of heat in summer
- provide the reserve of (possibly) hot water which is required for the fog production system which is also to be installed in the building Figure 30 shows a possible arrangement of the system

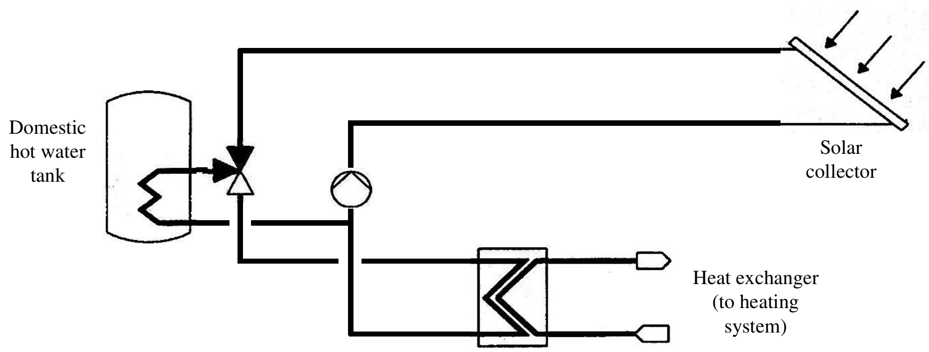


Figure 30 : Connection between the HVAC plant and the solar plant

C. Direction of ventilation
It was anticipated at this stage that low speed ventilation could help in maintaining adequate and stable fog conditions. This issue was to be tested in the climatic chamber of the University of Liège. It is still unclear whether the direction of the ventilation stream should be downwards (ie to ventilate from the ceiling) or upwards (ie to supply air at ground level). The latter is equivalent to the creation of a displacement ventilation system.

D. Is cooling of the offices required ?
It is clear that the offices area should be heated in wintertime. The question is concerning the necessity of cooling this zone of the building is summertime. To answer this question, a number of additional thermal simulations were conducted for critical periods of the year. They showed, together with obseravtions during the 2001 summer that the overheating risk was present in the building. Consequently, cooling of the offices through the floor would be made possible.

E. Overall control of the HVAC system
As can be seen from the different systems proposed and from the questions which are still to be solved, the global system appears as quite complex and, as a consequence, the overall process control might offer some complexities as well.

4.3. The selected HVAC scheme

From the different schemes proposed here above and taking into accoutn the constraints of the project (among others budgetary constraints), a compromise scheme was designed as a collaborative effort between the research team and the HVAC company. The selected scheme, which will be implemented, is given by figure 31.

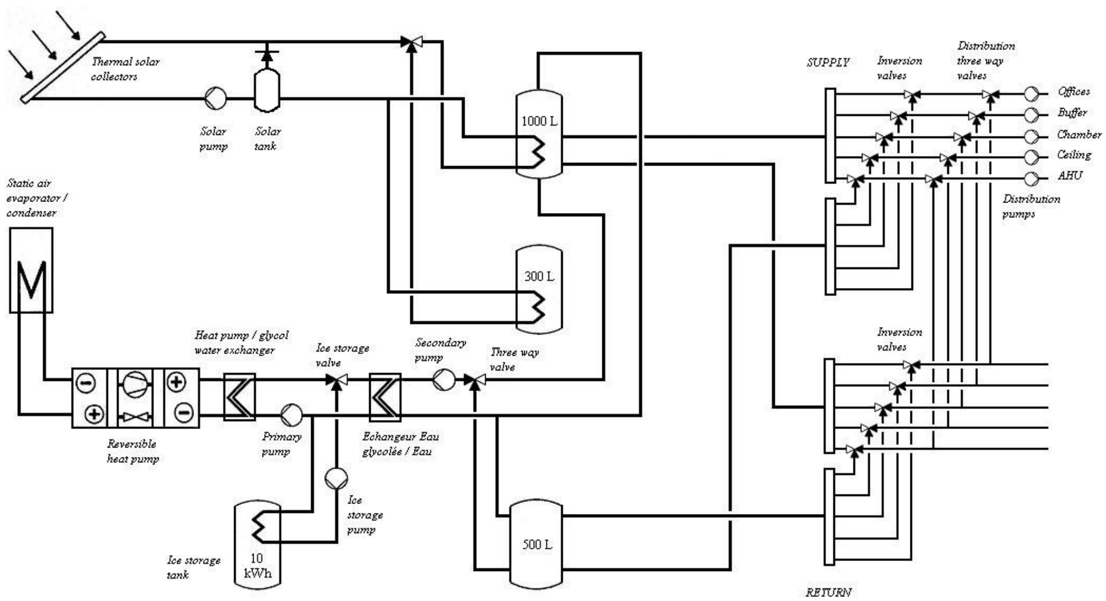


Figure 31 : Final design of the HVAC system of FUL fog chamber building

This scheme identifies the following components:

- the solar collectors
- the reversible heat pump/cooling machine: heating power: 8 kW; cooling power: 6 kW
- three storage tanks: 300 l for spraying water, 1000 l for the heating system, 500 l for the cooling system
- an additional heat exchanger between the reversible heat pump and the heating/cooling distribution circuit. The purpose of this heat exchanger is to avoid freezing of the circuit when the machine is working in cooling mode
- thermostatic control of each heating/cooling circuit.

At this stage, the simulation engine was used again in order to:

- optimise the thermal solar collectors area: a 15 m² area was found optimal
- optimise storage tanks volumes: calculations resulted in a 1000 l hot storage and a 500 l cold storage
- check the installed power, which was sized from the previous analysis
- calculate the relative contribution of the solar system and of the heat pump to the heating of the building. Results indicate that the total heating demand of the building amounts to 8000 kWh. Contribution of the solar system represents 50% of the total heating demand.
- Calculate the productivity of the photovoltaic panels: 2000 kWh (electrical energy)
- Assess the possibility of simultaneous heating and cooling of the building, even in the absence of solar energy. In this case, the selected scheme prevents direct simultaneous use of the energy at the evaporator and at the condenser. Instead, sequential use and storage of energy in the tank was considered as a solution. Simulation results show that, even in severe conditions, a 15 minutes period between each switch of the reversible heat pump was enough to accumulate heating or cooling energy for the period to come.

The selected final HVAC design is originating from both a priori choices and simulation outputs and is characterised by the following features:

- solar thermal collectors: 14.4 m²
- hot water storage: 1000 l
- cold water storage: 500 l
- radiating floor: the floor heating / cooling system is made of polyethylene pipes embedded within the mortar of the slab. In order to provide the maximum flexibility, three independent loops were created :test room, buffer space and offices
- ventilation system: the ventilation system is a "classical" air handling unit, working with or without recirculation and made of the following components : filter, heating/cooling coil, humidifier, fan. The air handling unit is sized for 1000 m^3/h and the heating/cooling coils will be connected to the heat and cold storage associated to the heat pump (see below).

4.4. Design of the ventilation system

As mentioned by table 2, the ventilation system was to be installed in both the test room and in the buffer space. The primitive function of the ventilation system was to provide climate control in both rooms. The idea of supporting fog production and duration by an adequate upwards or downwards ventilation was tested previously in the Liège chamber (Aparecida Silva and Hannay, 2001). It was also calculated by simulation (Kelly, 2001c) and both investigations demonstrated that ventilation was detrimental to fog stability. Consequently, this idea was left out. On the other hand, last testing results from Liège showed (Aparecida Silva and Hannay, 2002) that production of fog **inside** the ventilation system could be a possible alternative solution to the previous one where all nozzles were located in the room.

Consequently, an additional objective was defined for the ventilation system : to allow the **controlled** production of fog inside the ducting system. In this case, fog production control can be performed by two methods :

- by sequencing (on/off control) the activation of nozzle
- by mixing fog charged air with "dry" air before introduction in the chamber.

Preliminary testing in Liège also showed that a good method to introduce fog (by ventilation) in the chamber makes use of perforated ducts, situated either close to the floor or close to the ceiling of the test room.

The design of the ventilation system was carried out taking into account these preliminary results and also the first objective listed above. This results in the scheme given by fig. 35, which shows the principle of the ventilation system. The scheme identifies the following components :

- an Air Handling Unit made of
  - a filter
  - a coil which can work in heating mode or in cooling mode
  - a variable flow rate fan (from 300 m^3/h to 800 m^3/h)
  - a supply ducting circuit allowing to independently supply air to the test room and/or to the buffer space
  - an extraction ducting circuit allowing to remove air from the test room and/or from the buffer space
  - a recirculation ducting circuit
  - external air inlet and outlet.

The room air supply is further divided in two branches (in the technical room) : one branch is equipped with a nozzle and the other is not and the connection of both branches allows to mix "fog-charged" air with dry air.

Before entering the test room, the ducting is again divided into 2 branches, one to supply air from the top of the chamber, one to supply air from the bottom. Afterwards, both branches are divided, partly inside the buffer space, partly in the test room in 4 ducts in order to spread the air supply on the largest possible area.

A reverse configuration holds for the extraction outside the test room.

To control the flow in the different branches of the ducting, the system is equipped with 11 dampers with the following functions (see Figure 32 for location of the dampers) :

C_1 = outside air inlet control
C_2 = recirculation air inlet control
C_3 = buffer space supply control
C_4 = "fog" charged air ratio control
C_5 = "dry" air fraction control
C_6, C_7 = floor/ceiling supply control
C_8, C_9 = floor/ceiling extraction control
C_{10} = buffer space extraction control
C_{11} = outside outlet control.

C_1 to C_5 are motorized dampers while C_6 to C_9 are manual dampers.

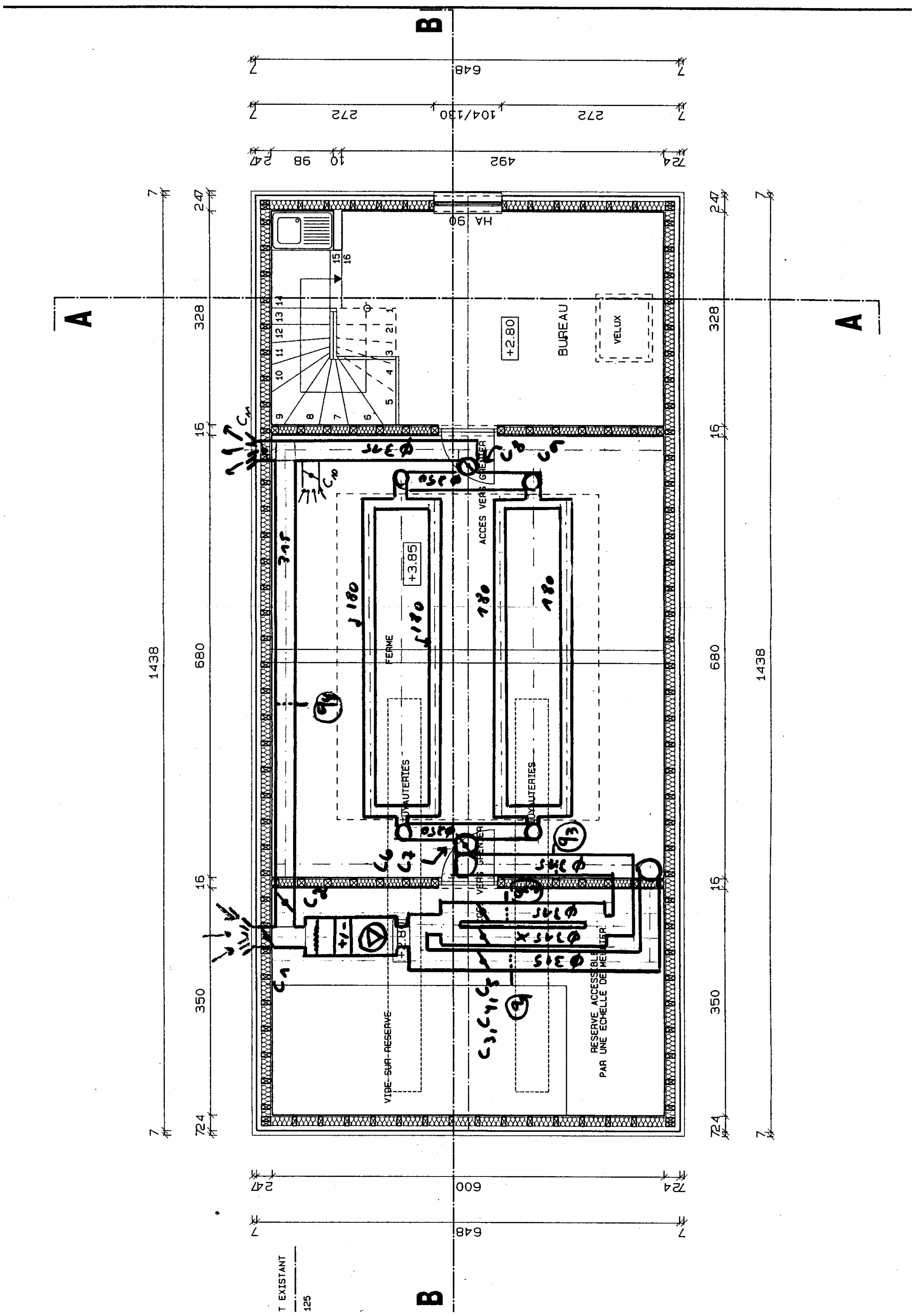


Figure 32 : Principle scheme of the ventilation system.

4.5. Design of the electrical system

As mentioned hereabove, the electrical system was designed in-house. The design was elaborated from the needs to be encountered in the building. The survey ends up with the following circuits:

- computer
- appliances
- lights in the offices
- lights in the technical room and buffer
- lights in the attic
- lights in the fog chamber
- alarm system
- meteorological station
- appliances offices ground floor
- appliances offices first floor
- appliances technical room
- appliances attic
- appliances buffer
- photovoltaic system
- hot water production
- HVAC system
- Heat pump
- Monitoring system interfaces
- Compressors of the heat pump
- Fog production pump

The different circuits were organised according to the functional scheme represented by Figure 33.

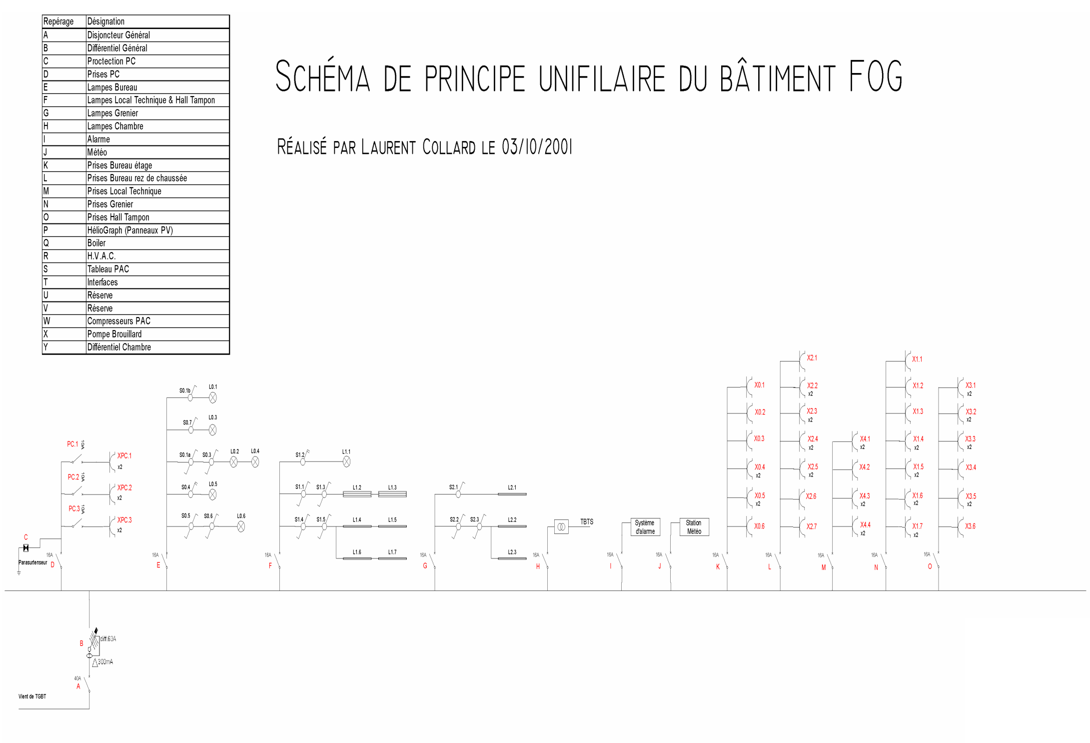


Figure 33 : Functional scheme of the electrical system

5. Design of the fog chamber and fog production system

5.1. Design of the fog chamber

The design of the fog chamber was also the object of investigation in the elapsed months. Different technical solutions were identified and were the object of a simulation-based comparison performed by partner Ustrath (Kelly, 2001d) .

The selected variants were:

- glass envelope
- plexiglass envelope
- wooden structure
- masonry structure
- steel + insulating material structure

A summer day and winter day simulation was run for each construction type and the performance assessed based on air and surface temperatures and plant energy consumption. The simulations are run using a characteristic North-European climate.
The simulations consisted of holding the air inside each test room to a fixed value between 07:00 and 13:00 using a coupled HVAC system, underfloor heating and heating of the buffer space. Lighting is assumed to be on between 11:00 and 12:00, with 500W of gains entering the test chamber.
The summer set point is 15℃ while the winter set point is 10℃ (the HVAC system's low flow rate causes it to stuggle in reaching 10℃ in summer). The flow rate from the HVAC system is 350m3/h, while the floor has a heating/cooling capacity of 4.5kW.

5.1.1. Winter simulation

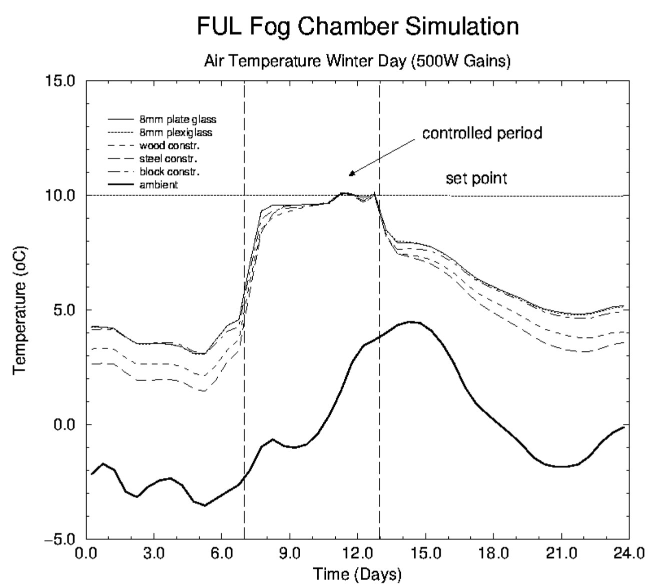


Figure 34: Evolution of the air temperature in the chamber, winter case

Figure 34 shows the variation in air temperature during the winter day simulation. The immediate point to note is that during the controlled period, the performance of all the constructions is very similar. The test room air temperatures associated with the plate glass and plexiglass constructions (as expected) respond most rapidly to heat input. During unheated periods the air temperature associated with the insulated steel and wooden constructions are 1-2℃ lower than the uninsulated homogeneous, glass, plexiglass and block constructions.

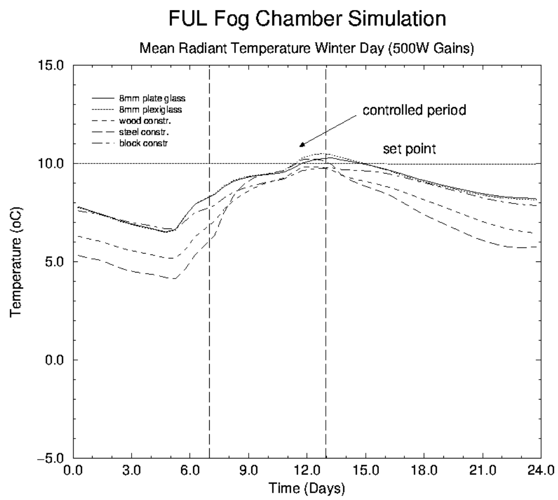


Figure 35 : Evolution of the mean radiant temperature in the chamber, winter case

Figure 35 shows the mean radiant temperature for the centre of the room during the winter day. Radiant temperature lags behind air temperature, with the plate glass and plexiglass constructions performing slightly better than the other three, in that they respond more rapidly to heating action.
The mean radiant temperature of the steel construction is as much as 4℃ less than the air temperature at the beginning of the heating period. The glass and plexiglass constructions are around 2℃ less.
All the mean radiant temperature are within +/- 0.5℃ of the air temperature by the end of the heating period.

5.1.2. Summer simulation

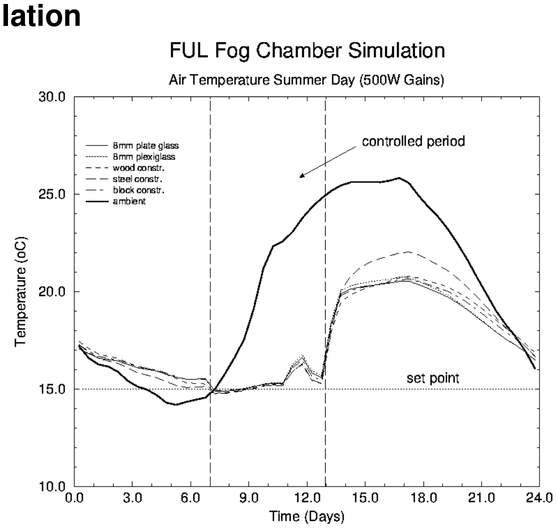


Figure 36 : Evolution of the air temperature in the chamber, summer case

Figure 36 shows the variation in air temperature during the summer day. Again, it is immediately apparent that the air temperatures, during the controlled period, are very similar for all the constructions. Looking more closely at the period of internal gains 11:00 - 12:00 it was hoped that the more massive block construction would "damp out" temperature fluctuations. This is not the case: the damping effect is very slight, with a 0.5°C reduction in peak temperature during gains between the block construction and the light plexiglass construction. Outside the controlled period the air temperature associated with the steel construction is 1-2°C higher than the other constructions, this requires some further investigation.

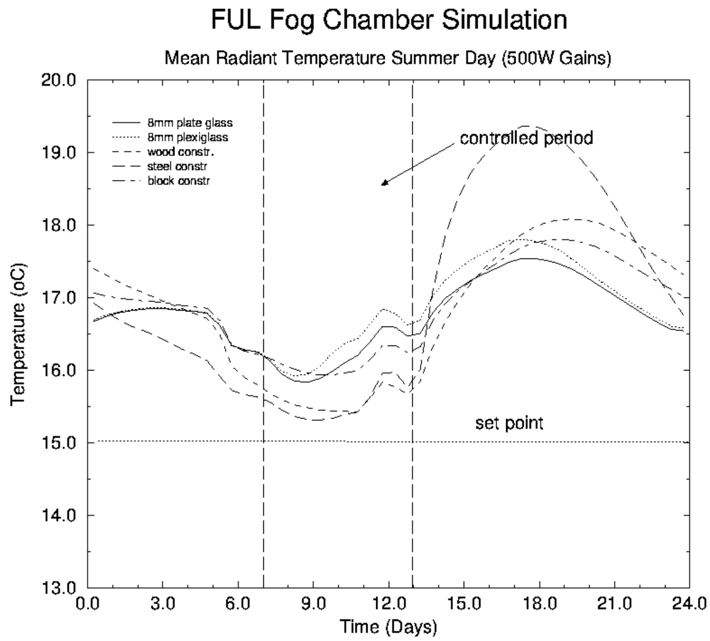


Figure 37 : Evolution of the mean radiant temperature in the chamber, summer case

Figure 37 shows the mean radiant temperature at the centre of the room. The performance of the constructions is reversed compared to the winter case, with the glass and plexiglass mean radiant temperatures being up to 1°C warmer than the air temperature during the controlled period. The wooden and steel insulated structures perform slightly better, with their radiant temperatures being the closest to the air temperature. Again note the curious behaviour of the steel-insulation construction surface temperature outside the controlled period. The analysis of heating and cooling energy consumption was inconclusive as there was very little difference between the energy consumption associated with each construction. This will require further simulations over a longer time period.

The simulations indicate that there is very little difference in terms of environmental performance between the 5 constructions examined.

*It should be noted that the floor construction remained the same for all 5 constructions and this will tend to be the dominating factor in terms of thermal mass within the test room.
*The plate glass and plexiglass constructions performed well in winter heating mode but less well in summer cooling mode.
*The reverse was true for the insulated wood and steel constructions.
*Overall in terms of test chamber performance the wall material has little effect.
*Selection of materials should therefore be done based on other factors e.g.
internal reflections with glass and plexiglass constructions during experiments, effects of moisture absorption in wood and block constructions, requirements for visibility of experiment (glass and plexiglass, etc.).

Given that results, it was decided to select a **wooden structure** for the chamber. Additional advantages indeed appear interesting to consider:

- execution speed
- good air and water tightness
- modularity (the whole chamber will be made of modular components)
- good structural resistance allowing to hang ceiling panels and fog production tubing

5.2. Design of the radiant ceiling system

As shown by table 2 a radiant ceiling was selected in the climate chamber. The goal of this element, in association with the floor heating system, was to contribute to the control of the temperature gradient in the test room. The idea was to control the interaction between the floor and the ceiling as a "master-sleeve" relationship (floor = master; ceiling = sleeve).

The ceiling (Figure 38) is made of 6 aluminium panels (4.8 x 0.6 m) in which circulation of water is provided (radiating ceiling, heating or cooling). The panels are separated by gaps which were initially designed as supply inlets for the ventilation system. Results from testing in Liège showed that this method was detrimental to fog stability and homogeneity (see above)

Consequently it was decided to fill these gaps with PVC plates in order to provide a totally air-tight and water tight envelope.

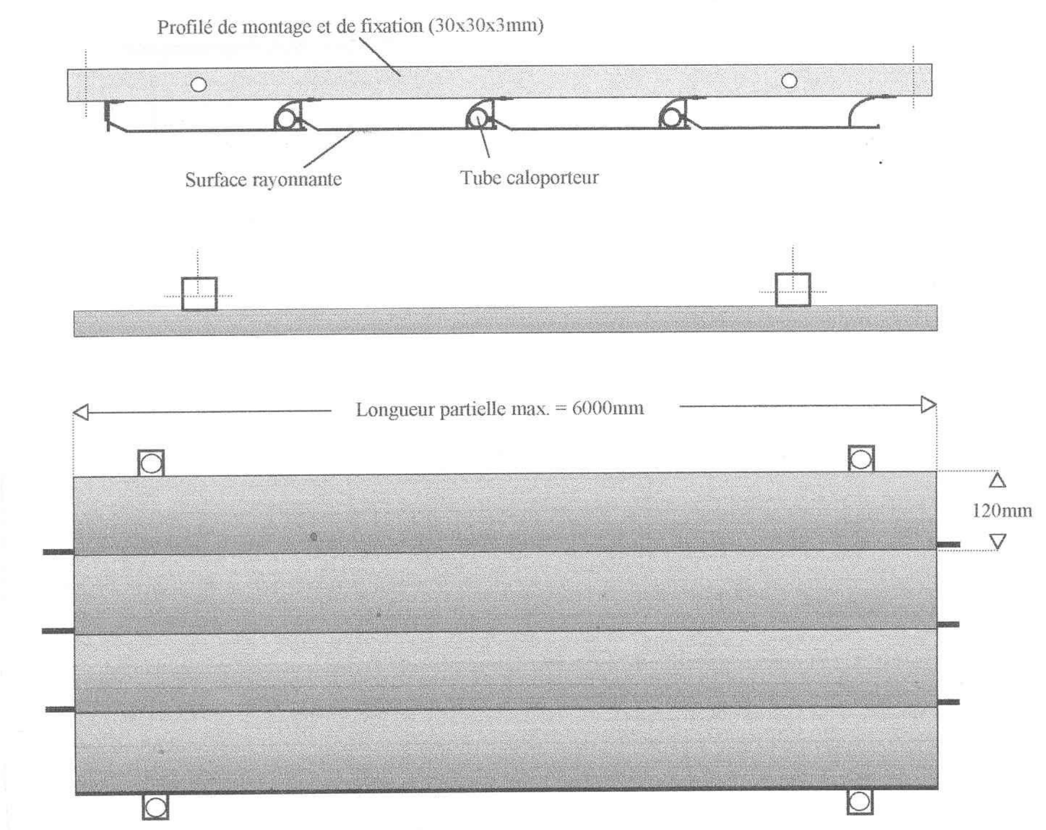
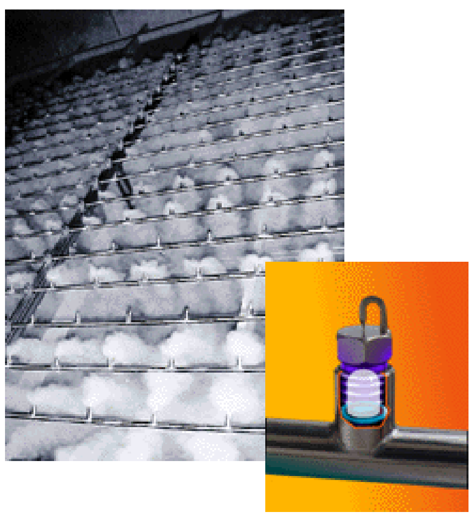


Figure 38 : Scheme of the radiant ceiling elements

5.3. Design of the fog production system

5.3.1. General presentation of the fog production system

As its name indicates it, a spray fog is a collection of droplets obtained by pulsing some liquid water with high pressure in a network of pipes provided with adequate nozzles.
The concept of spray fog is simple in theory: high pressure water is forced through nozzles which atomize the water into tiny fog droplets. Naturally, quite other thing staying equals, notably the atmosphere in which we produce the fog, the type of water, i.e. its degree of mineralization, its temperature and the used pressure, the type of nozzles as well as their number constraint strongly the obtained droplet size distribution and then the optical properties of such a fog.
Referred by Serezat (1997), the fog chambers of the LRPC was initially provided with impaction-pin nozzles manufactured by Mee Industries Inc. The following pictures (Figure 39) show such a (or very similar) impaction-pin nozzle[1].



MeeFog™ impaction-pin nozzles have a 0.006 inch orifice diameter ($\phi = 152$ µm) and produce fog droplets in the range of 11 microns in diameter (surface mean diameter).

Operating with 1000 psi pressure (1 psi = 6895 10^{-5} bar), manufacturer claims that such a impaction-pin nozzle generates more than five billion fog droplets per second in the range of 10 microns in diameter.

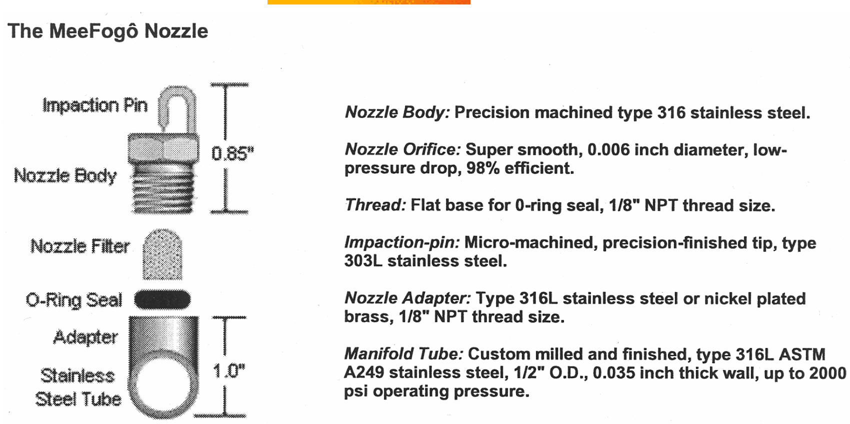


Figure 39 : Detailed views of the impact pin nozzles

According to this type of impaction-pin nozzle, (Serezat ,1997) proposes the following relationship (a little bit modified) :

[1] Both pictures are available on the Mee Industries Inc. web site at the following address: http://www.meefog.com/hvac/hvac.html.

(*) $$d_{mm} = 10^{-3} B \sqrt{\frac{\sigma_s}{P}} \phi$$

where

1. d_{mm} ≡ mass mean diameter (µm)
2. ϕ ≡ orifice diameter of the spray nozzle (µm)
3. σ_s ≡ surface tension of the liquid phase (dyn/cm)
4. P ≡ operating pressure (35/70 bars)
5. B ≡ coefficient assumed constant (cm$^{-1/2}$)

Example. Using pure water (σ_w = 72 dyn/cm at 20 °C), the MeeFog™ impaction-pin nozzles (ϕ = 152 µm, P = 72 bars) supplies: d_{mm} = 0.152×B µm (d_{mm} = 10 µm ⇒ B = 66 cm$^{-1/2}$).

5.3.2. Operating pressure effect

According to (*), if the operating pressure is multiplied by a positive real k the mass mean diameter d_{mm} is divided by the square root of k. So, operating with $P = 35\ bars$ and $P = 70\ bars$, we have:

$$d_{mm}(70) = \frac{1}{\sqrt{2}} d_{mm}(35)$$

5.3.3. Surface tension effect

According to the literature, the surface tension of a droplet of pure water depends mainly of its temperature in the range 0 °C – 40 °C. On the other hand, at constant temperature, the surface tension of a solution varies linearly with its molality. As a consequence, the surface tension of a droplet of solution at temperature t varies linearly with both temperature and molality.

5.3.4. Temperature effect

The surface tension of *pure water* is σ_w = *76.10 dyn/cm at 0°C*. Pruppacher and Klett (1980) convey the following relationship suitable in the range of 0 °C – 40 °C:

$$\sigma_w = 76.10 - 0.155t$$

where t is given in °C.

5.3.5. Salt dissolution effect

The variation of surface tension due to the dissolved part of the CCN is a function of the concentration. The *molality* is defined as the number of moles of salt dissolved in 1000 g of pure water:

$$\Xi = \frac{10^3}{m_w} \times \frac{m_s}{M_s}$$

Pruppacher and Klett (1980) refer that Hänel (1980) suggested the following empirical relationship for the surface tension of a saline solution:

$$\sigma_s(\Xi, t) = \sigma_w(t) + b\Xi$$

where $b_{NaCl} = 1.62$ dyn/cm and $b_{(NH_4)_2SO_4} = 2.17$ dyn/cm.

Example. A small nucleus of NaCl having a mass $m_s = 10^{-16}$ g (the mass of a large nucleus would be about $m_s = 10^{-13}$ g) is completely dissolved in a water droplet. According to (Dufour and Defay, 1963) the corresponding surface tension of the solution is given as: $\sigma_s\left(m_s, t\right) = 76.1 - 0.155t + 56.72\frac{m_s}{d^3}$

The typical diameter of a fog droplet is at least 1 µm. So, in the better case (t = 0℃, large nucleus) the ratio $m_s/d^3 \approx 10^{-1}$ makes the surface tension close to 80 dyn/cm.

Any case, referring to (*), as soon as the magnitude of σ (dyn/cm) equals the magnitude of P (bars) the term $10^{-3}\sqrt{\sigma/P}$ is more or least constant. So, the droplet mass mean diameter at the outlet of the spray nozzle is proportional to its orifice diameter: $d_{mm} = cons\tan t \times \phi$.

5.3.6. Summary

Neither surface tension nor operating pressure have a significant effect on the mass mean diameter of the droplet leaving the impaction-pin nozzle, at least while the mentioned parameter B remains constant. Such a formula cannot explain why spray fogs produced with demineralized water have a short lifetime and show “camel” spectra. Indeed, as soon a droplet is formed and freed in a closed chamber its evolution is leaded by some thermodynamic considerations, i.e. the ambiance of the room.

The fog production system provided by partner Dutrie was installed in the building according to the scheme given by fig. 40. The high-pressure pump was installed in the technical room, next to the 300 l hot water storage. The pump is connected to two lines, each one being equipped with 7 nozzles. Additionally, two lines were connected to the pump : one for calibration purposes, one to connect a nozzle situated in the ventilation system to the pump.

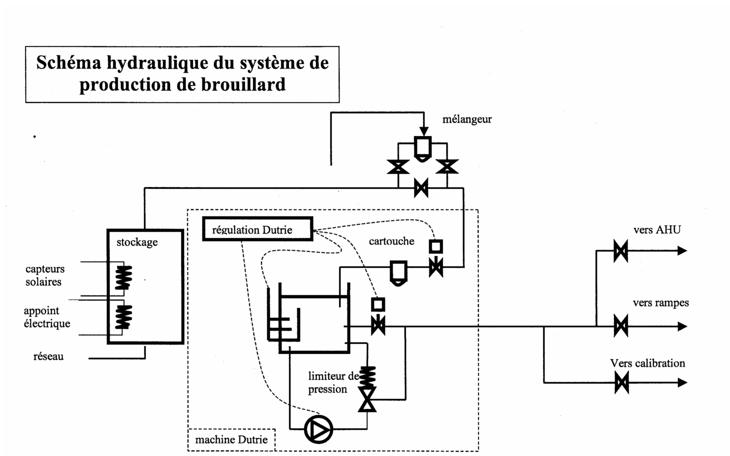


Figure 40 : Hydraulic scheme of the fog production system

6. Design of the monitoring and control system

The monitoring and control system was aldo developed as an in-house initiative.

6.1. Hardware

After a market survey, it was decided to select the “Agilent Technologies” VXI system as the hardware for data acquisition. The general structure of the data acquisition system is shown by figure 41.

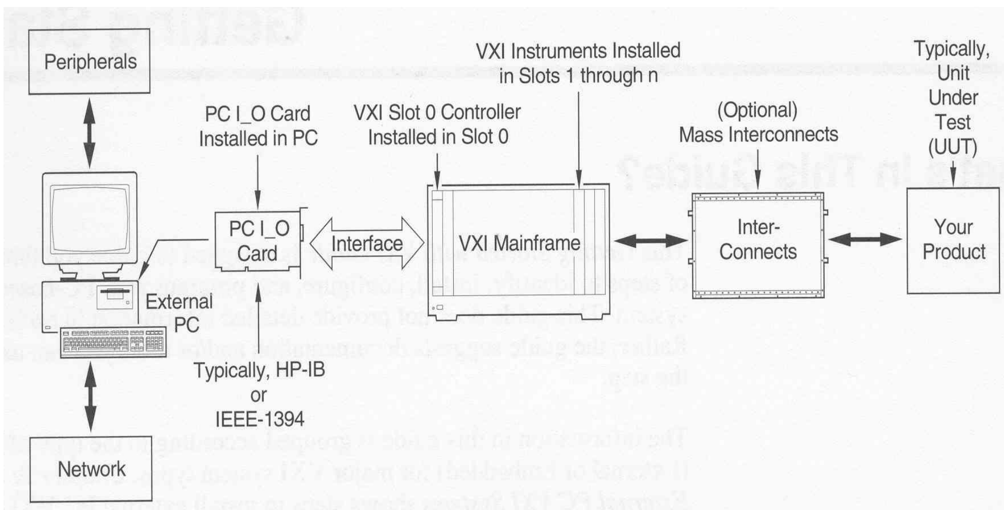


Figure 41 : General structure of the data acquisition system

From the specifications listed hereabove, the list of sensors and actuators could be established and is given in appendix which give: Label of the measurement, short label of the measurement, measured variable, type of sensors. As a summary, the list shows that the system is made of 172 measurement channels of which 159 are currently used. It also includes 16 analog outputs and 40 digital outputs.

The location of the different sensors (identified by their corresponding labels) is shown by figure 42 (heating and cooling system) and figure 43 (ventilation and fog production system).

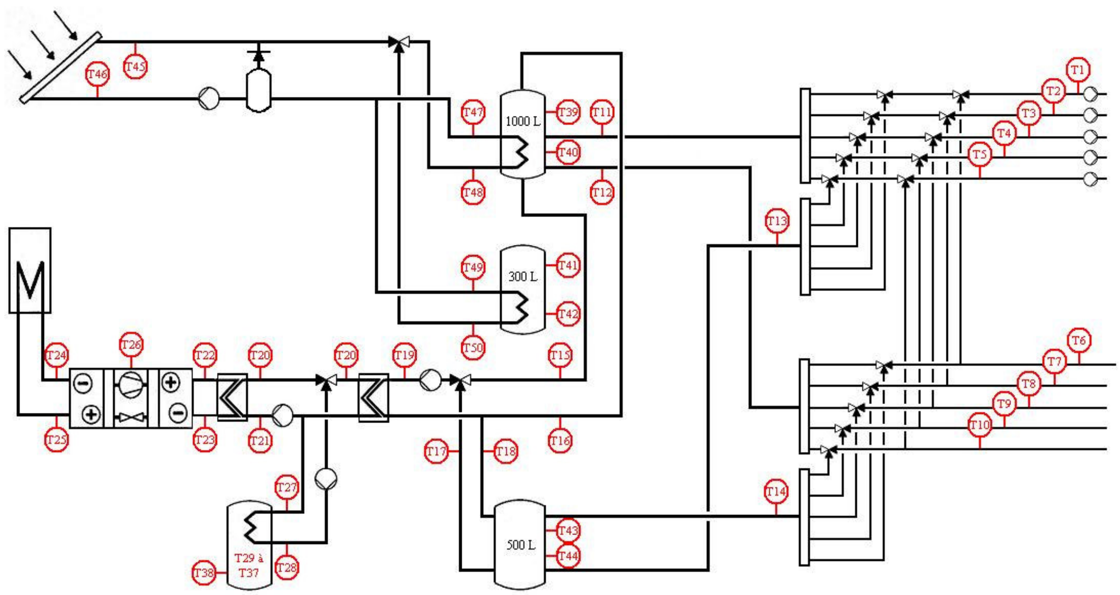


Figure 42 : Location of sensors for the heating and cooling system

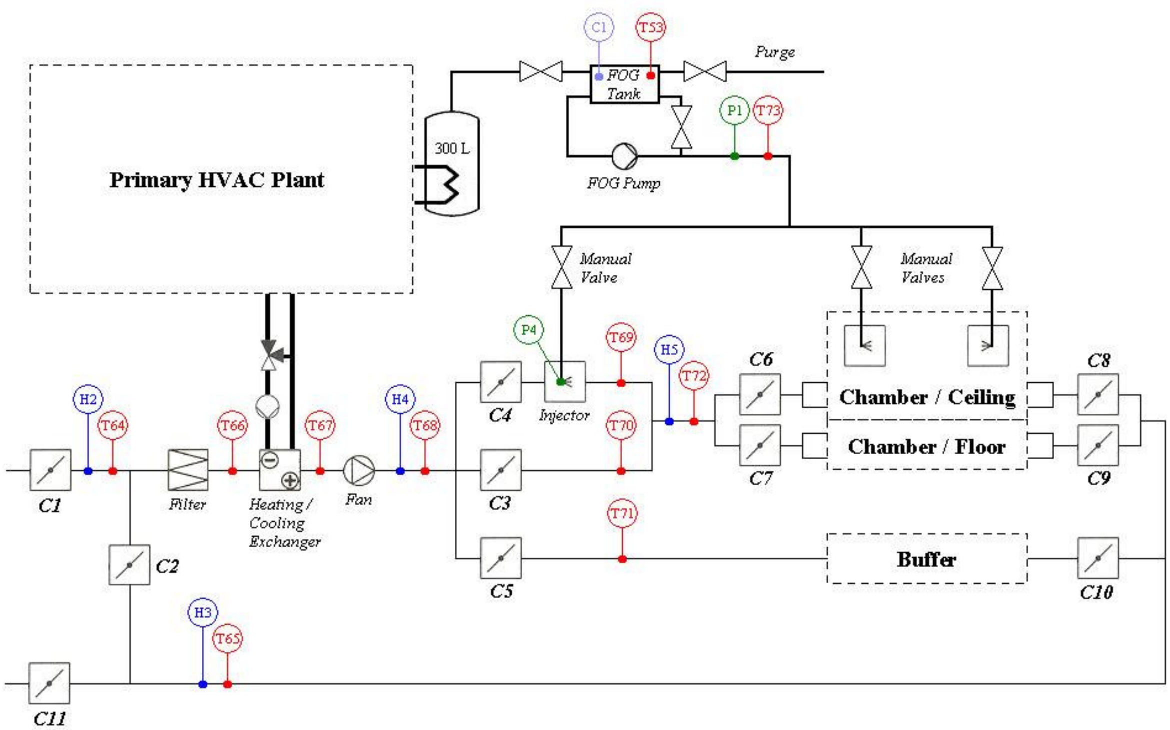


Figure 43 : Location of sensors : ventilation and fog production systems

6.2. Algorithms and software implementation

6.2.1. Management of the installation

6.2.1.1. Production

The management of the installation is closely related to maintain temperature set points of storages of water and ice. According to priorities imposed by the user, the equipments of production will function to maintain these points.
To manage the solar system, the user has the choice between the following priorities:

- Allowed discharge in the 1000L or not
- Allowed discharge in the 300L or not
- Priority to discharge in the 1000L or priority to discharge in the 300L

Moreover, it can switch on/off an electric heating in the middle of the fog tank (auxiliary heating).
To manage the reversible heat pump, the user has the choice between the following priorities:

- To maintain only the temperature set point instruction of the 1000L tank
- To maintain only the temperature set point instruction of the 500L tank
- To maintain only the energy set point instruction of the ice storage (charge mode)
- To maintain only the temperature set point instruction of the 500L tank by discharging the charged ice storage (discharge mode)
- To maintain all the set points (1000L, 500L, storage of ice) according to electrical tarification. The ice storage can then:
    - Not be used
    - Be used with full load (Full load mode)
    - Be used to manage the electrical peak consumption of the building (Demand limited mode)
- Priority to the heat pump operating mode or priority to the refrigerating mode (heating or cooling)

Because of the hydraulic connection of the heat pump, the system can only alternatively control one set point. (1000L, 500L or ice storage) at the same time. If the thermal demand of the building are too important, the set points should not be well maintained.

6.2.1.2. Storages

The instructions of storages are imposed freely by the user. According to the priorities of the production system, the set points will be maintained in an interval of ±1℃, for storage of water, and ±1kWh, for the storage of ice. Finally, two options are proposed to the user to impose the instruction of the storage of ice:

- The user can impose a fixed value (manual mode).
- The user can choose the automatic mode. This one consists in equalizing the energy set point with the total refrigerating demand of the previous day (during the on-peak hours of the electrical tarification).

6.2.1.3. Distribution

The water tanks of 1000L and 500L represent the energy reserves supplying the 5 distribution systems of the installation. On each circuit, two "three ways two positions" valves determine the hot source (1000L) or cold (500L) from which the distribution will be produced. A "three way proportional" valve controls the supply temperature of the application in function of the corresponding set point :

- Offices: Air temperature of the supervision room
- Buffer: Average of the 4 air temperatures of the buffer (not the probe above the room)
- Chamber: Average of the 5 middle level dry temperatures of the air-conditioned chamber
- Ceiling: Difference between the wall temperature of the ceiling and the ground (positive if the vertical heat gradient is positive bottom in top)
- AHU: Temperature of the air handling unit according to the selected mode:
    - The air temperature of the fan outlet
    - The air temperature of the mixed fog and air
    - The air temperature of the “dry” air (not wetted)
    - The average of the 5 middle level dry temperatures of the air-conditioned chamber

Each circuit is controlled by a PI regulator whose parameters can be chosen by the user according to his objectives. Moreover, the program allows 4 modes of distribution:

- Heating: The circuit provides only hot water to the application.
- Cooling: The circuit provides only chilled water to the application.
- Heating and cooling: The circuit provides hot or chilled water to the application according to demands.
- Nothing: The circuit turns in closed loop. The circuit provides neither hot heat nor chilled water.

An alarm was programmed on the first four distribution systems (Offices, Buffer, Chamber and Ceiling). When the supply temperature reaches a value between 40 and 45℃, the regulation valve is closed by 10% every 2 seconds as long as overheating is observed. If the supply temperature exceeds 45℃, the circuit is not controlled any more and distribution pumps are stopped. The elements of distribution (floors and ceiling) would not be damaged.

6.2.1.4. Software time step

In order to as well as possible manage the HVAC installation, the time step of the regulation was fixed to 5 minutes. Every five minutes, the program reconfigures the installation to maintain the set points of the equipment and the applications. This value was fixed according to the necessary time to move some valves to and according to the delay of the heat pump. Thus, instabilities are never observed.
The time step of the AHU control is smaller. Every 2 seconds, the system reconfigures the parameters and the commands of this part of the installation. The time step was fixed according to the speed of the thermal response of the system.

6.2.2. Control software

6.2.2.1. Introduction

FOGULAT 2.00 is the final version of the data acquisition and command software of the “FOG” building of the “Fondation Universitaire Luxembourgeoise “. The objectives of this program are:

- To carry out the data acquisition of installation HVAC of the building
- To carry out the data acquisition of the fog chamber (temperature sensors, heat flow, transmissionmeters...)
- To control the HVAC installation and to regulate all the distribution systems of the building
- To control the production of fog in the air-conditioned chamber by water spraying :
    - Directly in the room
    - In the AHU pipes
- To carry out the recording of the data (measurements, parameters of regulation...)

A GPIB cable connects the data logger to the PC in which FOGULAT 2.00 is implemented. The VXI system environment of work is HP VEE. HP VEE is the visual programming language which allows the communication between the PC and the VXI.

7. Construction of the building

After call for tenders, the construction work was contracted to the following of companies:

Foundations and infrastructures: Duvigneaud, Halanzy, Belgium
Wood structure and covering: Menuiserie Maquet, Recogne, Belgium
Pavement: Warnand, Wolkrange, Belgium
Sanitary and plumbing: Lambot, Aubange, Belgium
HVAC: Energy Savings System, Sprimont, Belgium
Solar thermal system: European Solar Engineering, Rochefort, Belgium
Solar PV system: Soltech, Leuven, Belgium

As mentioned above, installation of the electrical, monitoring and control system were carried out by the FUL staff.

The construction of the testing faciltiy took place between November 2000 and November 2002, accroding to the following schedule:

- November 2000 : foundations and access road (fig. 44)
- January 2001 : start of construction of the wooden structure (fig. 45)
- February 2001 : placement of solar collectors (photovoltaic and thermal) and placement of the roof covering (fig. 46)
- March 2001 : thermal insulation and internal partitioning (fig. 47)
- April 2001 : electrical system installation
- September2001 : installation of the HVAC system (fig. 48 and 49)
- October 2001 : development of the measurement and control system (fig. 50)
- January 2002: (final design of the fog chamber
- April 2002: construction of the fog chamber (fig. 51)
- May 2002: installation of the instrumentation
- July 2002: installation of the radiating ceiling panels in the chamber and painting of the walls (fig. 52)
- September 2002: installation of the Air Handling Unit (fig. 53)
- October 2002: installation of the ducting (fig. 54)
- November 2002: commissioning and first testing of the equipment (fig. 55)

The different steps of the construction is illustrated by the following pictures.

Figure 44 : Construction of the foundations of the building

Figure 45 : Construction of the wooden structure

Figure 46 : Placement of the roof and solar collectors

Figure 47 : Placement of thermal insulation and internal partitions

Figure 48 : Heat pump and storage tanks

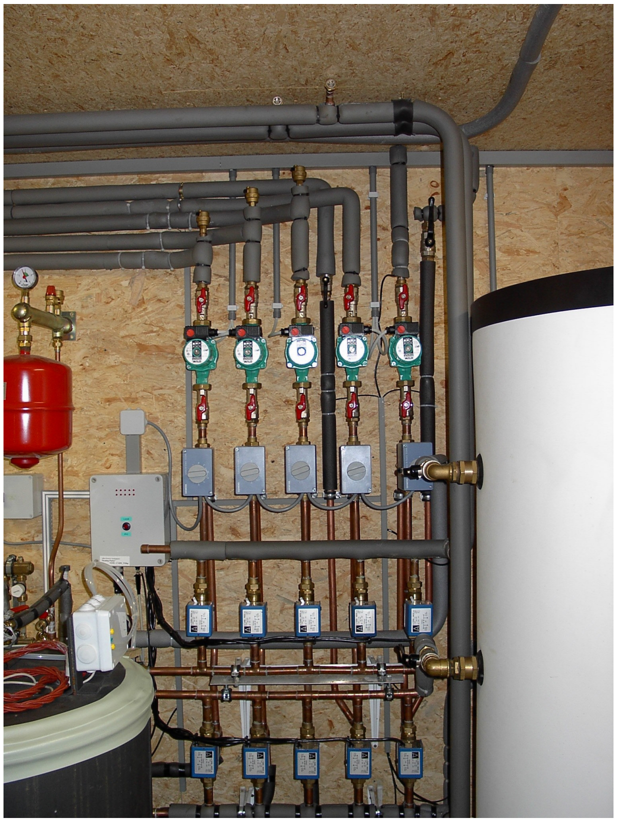


Figure 49 : Distribution circuits

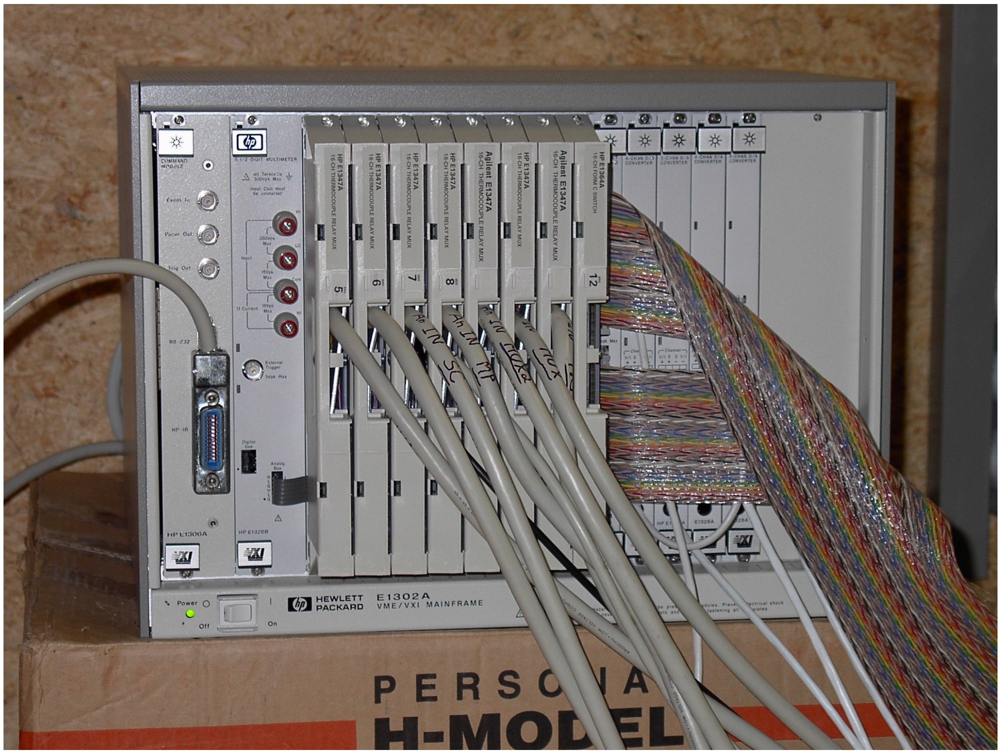


Figure 50 : Data acquisition system

Figure 51 : Fog chamber construction

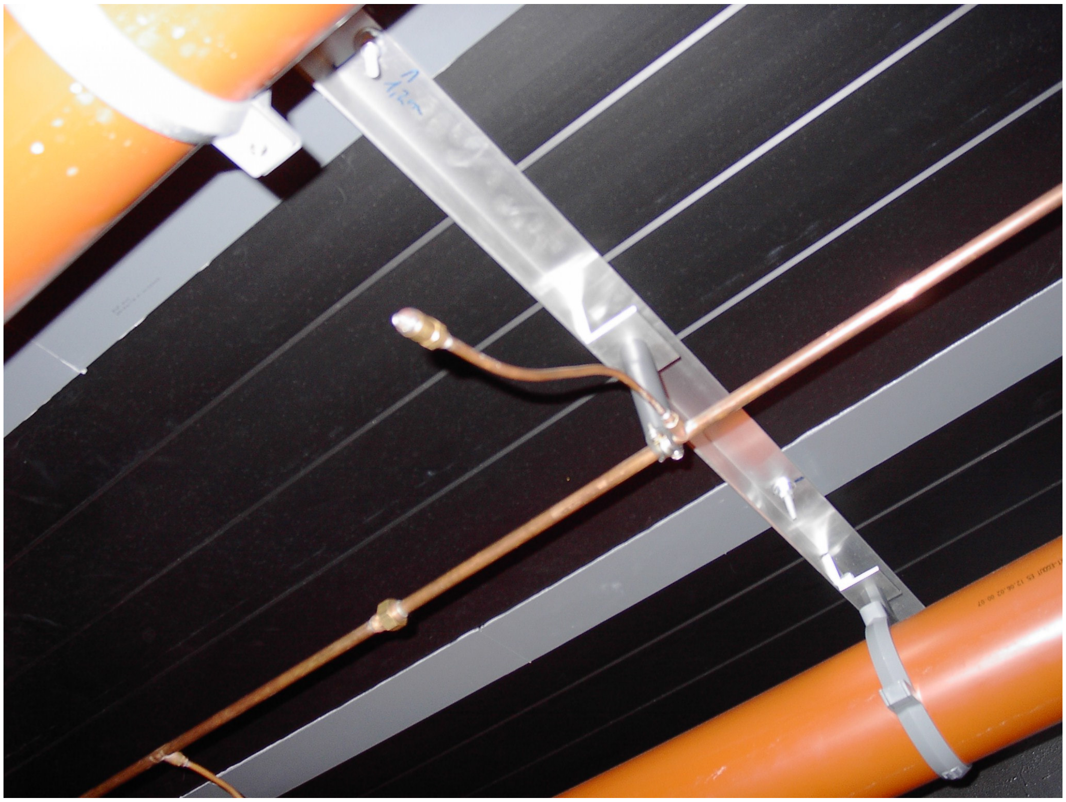


Figure 52 : Radiating ceiling panels and fog production nozzles

Figure 53 : Air Handling Unit and ducting circuit

Figure 54 : The ducting in the buffer space

Figure 55 : A first trial from the observation room

8. First tests of the building and of the fog production system

8.1. Introduction

The trials in the FUL fog chamber really began in early 2003. Indeed, the construction of the building, the installation of the chamber and its equipments (sensors) required a little more time than initially foreseen.

The first step of the testing phase consisted in the definition of an experimental program. Therefore, the sensible variables characterizing the process of fog production had to be identified.

First, it is necessary to distinguish the way of producing the fog of the way of air-conditioning the chamber. It is obvious that these two points of view each contain a certain number of factors presenting several levels (Figure 56 and Figure 57)

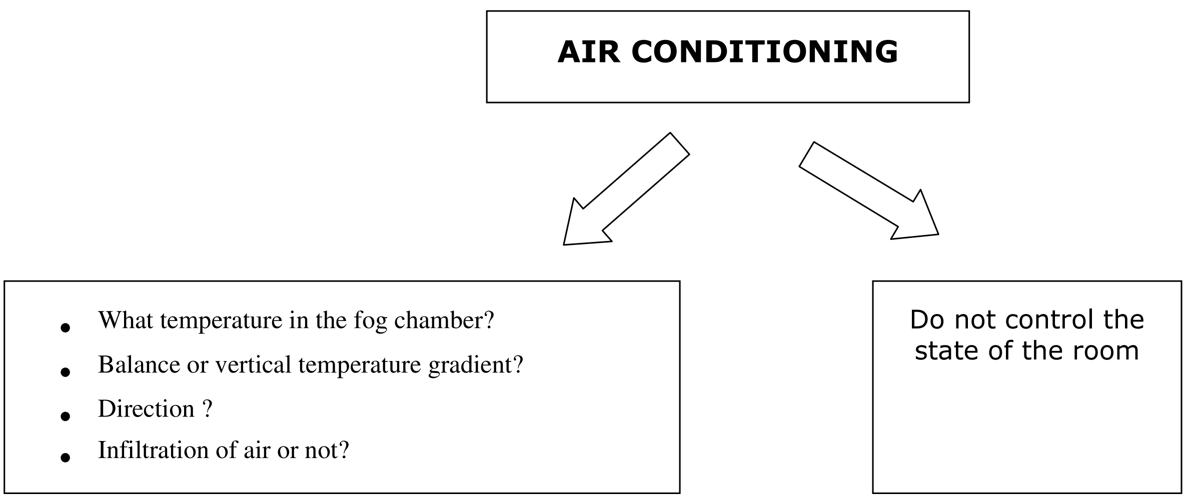


Figure 56 : Possibe room conditioning strategies

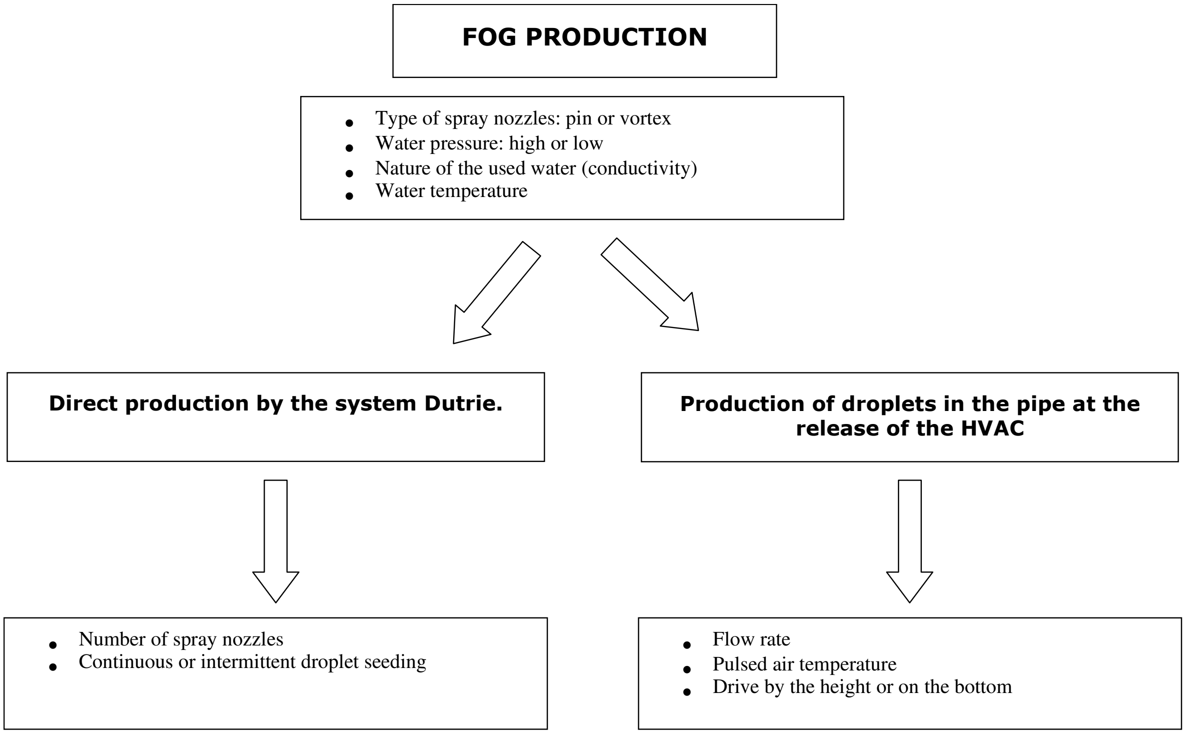


Figure 57 : Possible fog production strategies and associated variables

As the number of possible configurations is equal to the product of the levels taken by each of the identified factors, it is obvious that a sorting was imperative (i.e., the feeling of the operator played an important role).

8.2. Survey of the main operational variables

8.2.1. The production of the spray fog

Fog droplets (Figure 58) can be produced by feeding directly pipes provided with nozzles installed in the chamber (pulverisation-based system) or by sowing the air-conditioning with droplets produced by one or two nozzles and then by venting this aerosol in the chamber via a network of ducts (ventilation-based system).

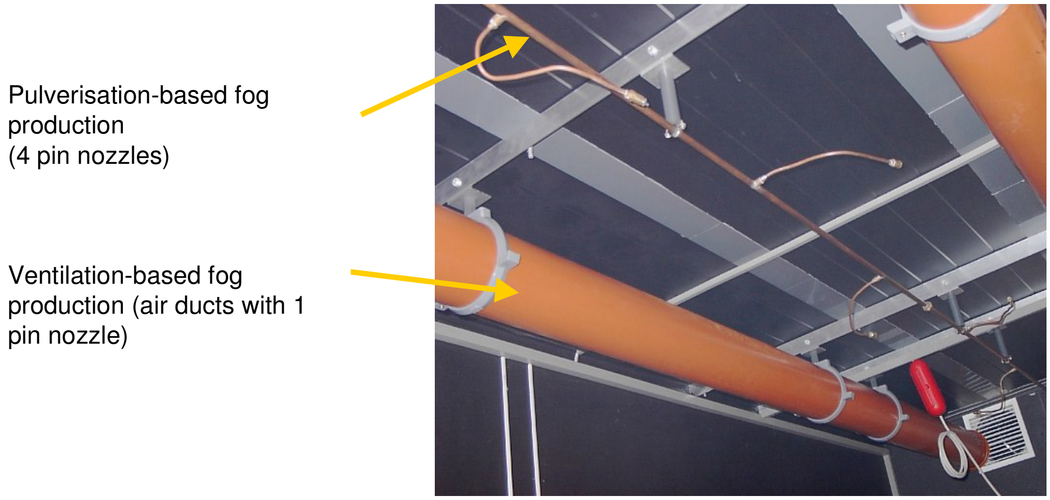


Figure 58 : Two systems for spray fog production

Additionally, two types of nozzles can be used: the so-called pin nozzles and the so-called vortex nozzles.
In the case of the pulverisation-based system, the number of active nozzles can vary from one to fourteen (currently four). The selected water pressure is 70 or 50 bars. Last but not least, the water temperature in the tank is maintained close to the air temperature in the chamber (currently 15 °C).
In the case of the ventilation-based system, one or two pin nozzles are located at the outlet of the ventilation system (Figure 59). The temperature of the aerosol must be imperatively greater or equal to the chamber air temperature (currently 15 °C).

Figure 59 : Fog production in the duct with ventilation

8.2.2. The control of the climate in the chamber.

The floor and the ceiling can be heated or cooled, if required simultaneously. In theory, a slight vertical pressure temperature gradient should oppose the gravity. In the room filled with droplets, some air of which we control the humidity and the temperature can be vented. Depending on the quantity and characteristics of infiltrated air, the resulting aerosol is quite different from the former.

8.2.3. Synthesis

By playing on the mode of production and on the air conditioning, it appears clearly that thousands of configurations are possible. The common sense of the physicist and the feeling of the operator allowed selecting some configurations giving stable fogs to levels of visibility chosen for their operational application.

8.3. The trials and their results

At once a remark is imperative: the installations evolved during time. Indeed, the fog chamber became operational only at the middle of December 2002. So, between the first attempts and the last ones (realized in March 2003) corrections and successive improvements were brought to the system. The comparisons are thus delicate to perform. In brief, although producing stable fogs as long as the user wishes is possible, a big validation work remains to be done.

8.3.1. Spray fog with pulverisation-based system

8.3.1.1. The number of active nozzles

Theoretically, the flow rate of any pin-nozzles is 5 l per hour. So, n nozzles running during t hours supply v liters of water dispersed into a large number of tiny droplets:

$$v = 5nt$$

Ordinary, t = 1/20 h and with n = 14 we find 3.5 l of water spread in 60 m^3 (the chamber volume), i.e. more than 5 g per cubic meter. It is well known that a natural fog contains of the order of 0.5 g of liquid water by m^3 of cloudy air. Of course, the drier the chamber the greater the duration of fog production required to saturate the chamber (the walls must be "wet"). As soon as the chamber is close to the saturation, it is no longer useful to use fourteen nozzles. It was decided to activate only four nozzles evenly placed into the room.

8.3.1.2. Natural fog dissipation

The experimental protocol consists in producing fog during a few minutes and to let it evolve "naturally", without action of the operator.

Figure 60 depicts a typical profile of fog duration when the chamber is not yet saturated (early morning or after few days without use).

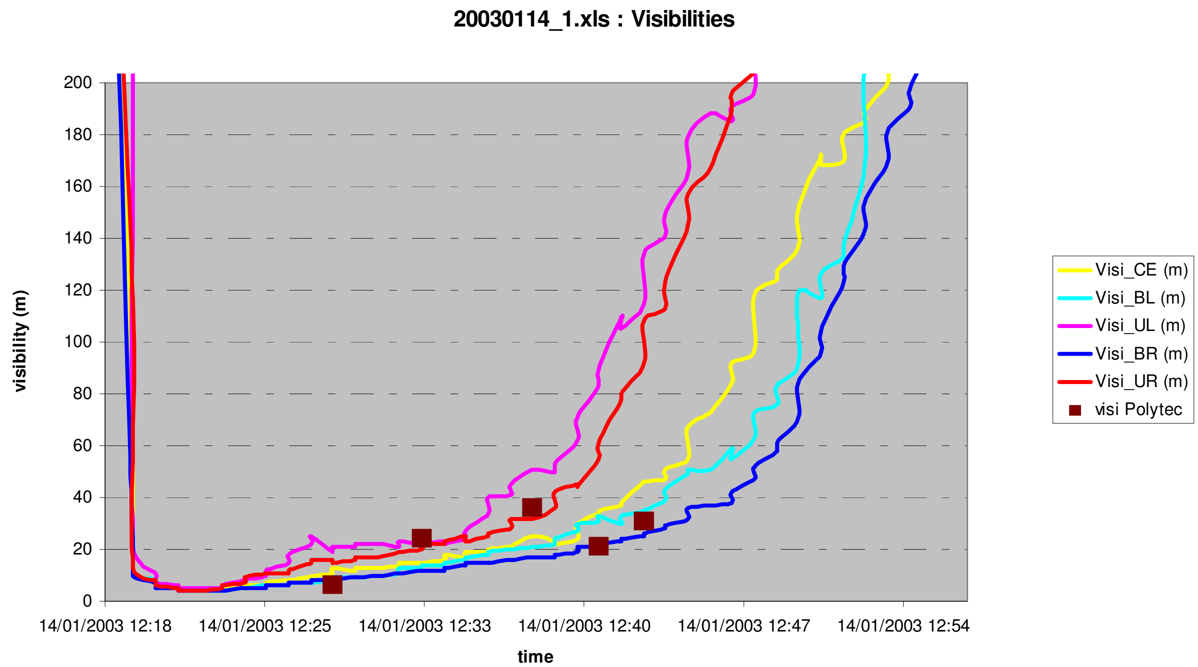


Figure 60 : natural fog dissipation into an unsaturated chamber

Figure 61 shows that the fog duration increases as the chamber becomes saturated. However, the homogeneity of the fog is not satisfactory and this is probably due to the too fast evolution of the visibility.

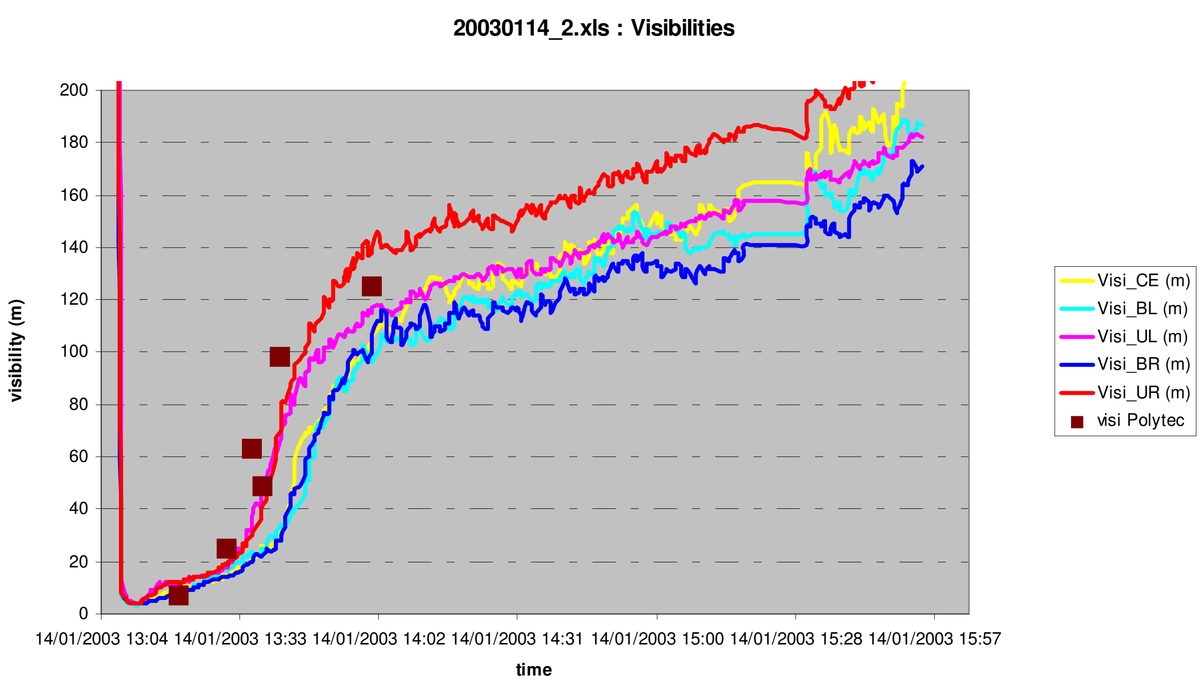


Figure 61 : natural fog dissipation into a saturated chamber

8.3.2. Fog production in the duct with ventilation

8.3.2.1. Configuration of the system

A shown by Figure 59, a single pin-nozzle was settled into the pipe at the release of the HVAC system. The injection of droplets in the pipe is continuous and the air flowrate (output of ventilation system) can be controlled (More or less strong opening of the dampers). Then the fog produced is vented in the room from the top either or from the bottom or both. As depicted by Figure 62, the aerosol vented in chamber from the bottom left (big arrow), moves according to the slim arrows and is exhausted outside. Such a pathway generates a certain heterogeneity into the chamber (the upper left transmissometer (identified by a yellow circle) records less droplets than the others).

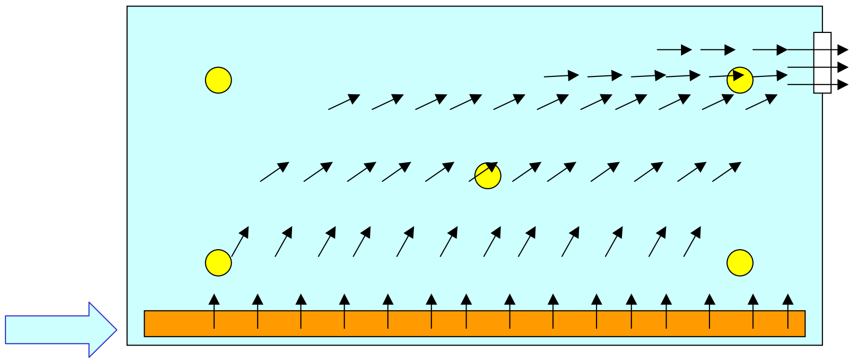


Figure 62 : Input and pathway of the fog pulsed in the saturated room.

A typical profile is depicted by Figure 63.

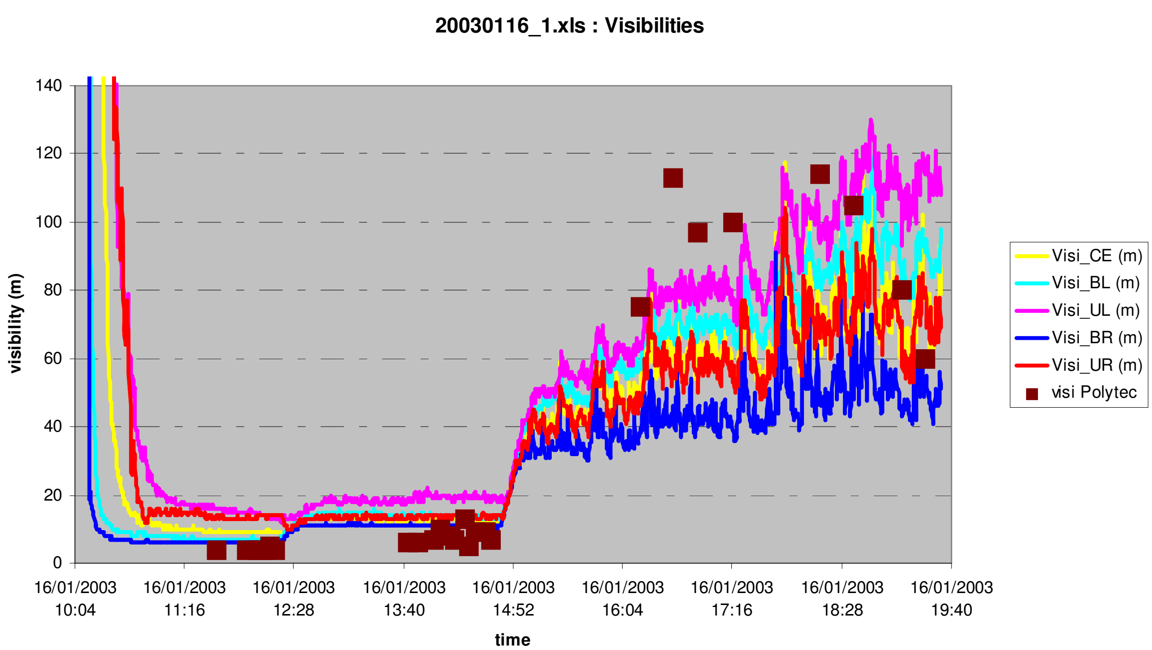


Figure 63: Fog duration and homogeneity (heterogeneity) associated with continuous fog production into the duct

It appears that the heterogeneity increases as the visibility increases (opening of the dampers).

8.3.2.2. The booster effect

The production of droplets in the duct at the outlet of the ventilation system associated to a good air flowrate, the temperature of which being controlled, seems to give good results. Then, a booster was placed in the room with the aim of homogenizing the fog produced. Rather curiously the results were sharply better.
According to Figure 64, the speed of the booster plays an important role in the homogenization of the fog. First, during about one hour, the selector is on the position 9 (max). The visibility increases and stabilize around 85 meters. Next, the selector goes down position 7 during about 30 minutes. The visibility increases a little bit. Next, at position 5, the visibility decreases sharply and increases slowly. At about 6:30 pm, the booster is stopped and the fog remains, with a high heterogeneity, up to 21 p.m.

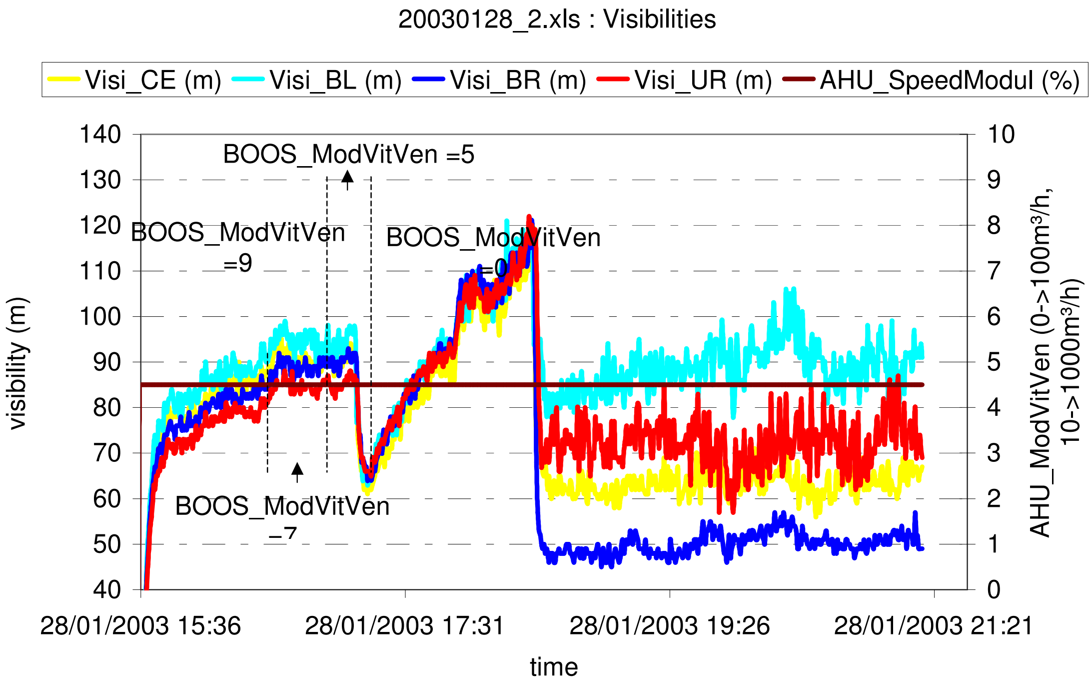


Figure 64 : Droplet size distributions

In all cases, it can be verified that the droplet size distributions remain compatible with those observed in natural fogs (Figure 65).

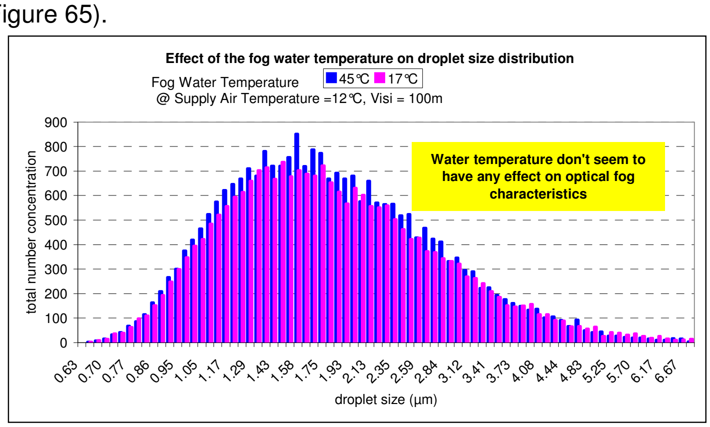


Figure 65 : Comparison of droplets distribution in natural and artificial fog

8.4. Synthesis

As a synthesis of the assessment of the evaluation criteria, the best fog production configuration achived so far includes the following characteristics:

– Fog production into the duct (1 nozzle)
– Continuous fog production
– Ventilation both from the bottom and the top of the chamber
– Use of a mixing fan in the chamber whose speed is reduced when reaching higher visibility
– Modulation of the air flow rate of the ventilation to achieve different levels of visibility

A testing protocol was also defined, including the following steps:

– 1st trial of the day : saturation of the chamber by fog production into the chamber (4 nozzles) in natural fog dissipation
– 2nd production into the chamber and when reaching 10m of visibility, commutation with the fog production into the duct (1 nozzles)

The tests achieved so far allowed to identify the current limitations of the approach.

8.5. Conclusions and current limitations of the approach

The first results were very satisfactory, especially in low visibility, in terms of duration, stability and homogeneity (really less than +/-10% expected !).

There are nevertheless a lot of things that should be better controlled:
- there is a need for more reproducibility to better understanding of the behavior of the system

Higher visibilities can be expected but currently there is no means to prove it due to measurements problems (transmissiometers still need to be improved)
Future perspectives for improving visibility control include:

- higher visibilities (>100m)
- radiation fog generation
- better appraisal of fog production into the chamber
- natural fog dissipation with thermal gradient control
- control of the visibility in closed loop

The major limitations observed up to now concern the following variables:

– Supply air flow rate
– Supply air temperature
– Fog water flow rate
– Fog water temperature
– Chamber temperature
– Transmissiometers measurements

9. Conclusions

The construction of the fog chamber prototype was the main objective of the FOG project. This development involved the construction of a totally new building on the FUL campus. In order to realize this construction work, a number of “strategic” choices were realized at the begin of the project:

- adoption of a professional building design approach
- use of a global environmental approach
- use of modern simulation tools in the design process.

The results of this work is now fully operational, as the conclusion of a continuous 2 years process, with the usual “problems” occuring in the construction of a building: delays, reorientation of some aspects of the design in the course of the project,…

Nevertheless, this activity of the FOG project can be considered as a success as all design criteria formulated at the beginning of the project could be met and as the time schedule available was more or less respected. The facility was fully operational after 30 months and an important testing phase could take place.

The main highlighting characteristics of this construction are:

- an improved fog chamber prototype showing efficient climate control
- a flexible testing facility with an unlimited number of potential applications in relation to climate control
- a high-level monitoring and control system with more than 150 sensors connected
- an ecological modern building ready for demonstration and visits, including the use of natural energy sources and material

As announced in the project proposal, a high number of research applications can benefit from this facility: energy management, air quality and aerosols, bio-indicators and agricultural research.

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Appendix: list of the sensors of the data acquisition system

Label	Application	Name	Type
C1	FOG	Water Conductivity	4-20mA
H1	METEO	Outdoor Air Humudity	4-20mA
H2	AHU Fresh Air	Air Humidity	Volt DC
H3	AHU Exhaust Air	Air Humidity	Volt DC
H4	AHU Fan	Outlet Air Humidity	Volt DC
H5	AHU Fog	Supply Air Humidity	Volt DC
P1	FOG	Supply Pump Pressure	4-20mA
P2	HVAC Ice Storage Tank	Energy Probe Pressure	Volt
P3	METEO	Atmospheric Pressure	VDC
P4	FOG	Injector Water Pressure	4-20mA
P5	CHAMBER	Differential Pressure 1	Volt DC
P6	CHAMBER	Differential Pressure 2	Volt DC
S1	METEO	Solar Radiation On Horizontal Surface	4-20mA
S2	METEO	Solar Radiation On Western Vertical Surface	Volt
T01	HVAC Offices	Supply Water Temperature	CTN
T02	HVAC Buffer	Supply Water Temperature	CTN
T03	HVAC Chamber	Supply Water Temperature	CTN
T04	HVAC Ceiling	Supply Water Temperature	CTN
T05	HVAC Coil	SupplyWater Temperature	CTN
T06	HVAC Offices	Return Water Temperature	CTN
T07	HVAC Buffer	Return Water Temperature	CTN
T08	HVAC Chamber	Return Water Temperature	CTN
T09	HVAC Ceiling	Return Water Temperature	CTN
T10	HVAC Coil	Retur Water Temperature	CTN
T11	HVAC Heating Collector	Supply Water Temperature	CTN
T12	HVAC Heating Collector	Return Water Temperature	CTN
T13	HVAC Cooling Collector	Supply Water Temperature	CTN
T14	HVAC Cooling Collector	Return Water Temperature	CTN
T15	HVAC Hot Water Storage	Supply Water Temperature	CTN
T16	HVAC Hot Water Storage	Return Water Temperature	CTN
T17	HVAC Chilled Water Storage	Supply Water Temperature	CTN
T18	HVAC Chilled Water Storage	Return Water Temperature	CTN
T19	HVAC Secondary Exchanger	Supply Water Temperature	CTN
T20	HVAC Primary Exchanger	Supply Glycol Water Temperature	CTN
T21	HVAC Primary Exchanger	Return Glycol Water Temperature	CTN
T22	HVAC PAC	Supply Primary Exchanger Temperature	CTN
T23	HVAC PAC	Return Primary Exchanger Temperature	CTN

T24	HVAC PAC	Return Static Air Exchanger Temperature	CTN
T25	HVAC PAC	Supply Static Air Exchanger Temperature	CTN
T26	HVAC PAC	Air Temperature	CTN
T27	HVAC Ice Storage Tank	Return Glycol Water Temperature	CTN
T28	HVAC Ice Storage Tank	Supply Glycol Water Temperature	CTN
T29	HVAC Ice Storage Tank	Temperature 1	PT500
T30	HVAC Ice Storage Tank	Temperature 9	PT500
T31	HVAC Ice Storage Tank	Temperature 6	PT500
T32	HVAC Ice Storage Tank	Temperature 4	PT500
T33	HVAC Ice Storage Tank	Temperature 3	PT500
T34	HVAC Ice Storage Tank	Temperature 7	PT500
T35	HVAC Ice Storage Tank	Temperature 8	PT500
T36	HVAC Ice Storage Tank	Temperature 2	PT500
T37	HVAC Ice Storage Tank	Temperature 5	PT500
T38	HVAC Ice Storage Tank	Energy Probe Temperature	CTN
T39	HVAC Hot Water Storage	Top Temperature	CTN
T40	HVAC Hot Water Storage	Bottom Temperature	CTN
T41	FOG Water Storage	Middle Temperature	CTN
T42	FOG Water Storage	Bottom Temperature	CTN
T43	HVAC Chilled Water Storage	Top Temperature	CTN
T44	HVAC Chilled Water Storage	Bottom Temperature	CTN
T45	HVAC Solar Collectors	Supply Temperature	Volt
T46	HVAC Solar Collectors	Return Temperature	CTN
T47	HVAC Solar Collectors - Hot Water Storage Side	Return Water Temperature	CTN
T48	HVAC Solar Collectors - Hot Water Storage Side	Supply Temperature	CTN
T49	HVAC Solar Collectors - FOG Water Storage Side	Return Temperature	CTN
T50	HVAC Solar Collectors - FOG Water Storage Side	Supply Temperature	CTN
T51	FOG Water Storage	Inlet Water Temperature	CTN
T52	FOG Water Storage	Outlet Water Temperature	CTN
T53	FOG Tank	Water Temperature	4-20mA
T54	METEO	Outdoor Air Temperature (Solar Building)	4-20mA
T55	BUILDING Meeting Room	Air Temperature	CTN
T56	BUILDING Offices	Air Temperature	CTN
T57	BUILDING Technical Room	Air Temperature	CTN
T58	METEO	Outdoor Air Temperature (FOG Building)	4-20mA
T59	BUILDING Buffer	Air Temperature (Top)	CTN
T60	BUILDING Buffer	Air Temperature (North)	CTN
T61	BUILDING Buffer	Air Temperature (South)	CTN
T62	BUILDING Buffer	Air Temperature (East)	CTN
T63	BUILDING Buffer	Air Temperature (West)	CTN
T64	AHU Fresh Air	Air Temperature	CTN
T65	AHU Exhaust Air	Air Temperature	CTN
T66	AHU Coil	Inlet Air Temperature	CTN
T67	AHU Coil	Outlet Air Temperature	CTN

T68	AHU Fan	Outlet Air Temperature	CTN
T69	AHU Wet Air	Supply Air Temperature	CTN
T70	AHU Dry Air	Supply Air Temperature	CTN
T71	AHU Buffer Air	Supply Air Temperature	CTN
T72	AHU Fog	Supply Air Temperature	CTN
T73	FOG	Supply Water Temperature	CTN
TF01	CHAMBER	Wet Air Temperature (Stake 1 Low)	CTN
TF02	CHAMBER	Wet Air Temperature (Stake 1 Middle)	CTN
TF03	CHAMBER	Wet Air Temperature (Stake 1 Top)	CTN
TF04	CHAMBER	Wet Air Temperature (Stake 2 Low)	CTN
TF05	CHAMBER	Wet Air Temperature (Stake 2 Middle)	CTN
TF06	CHAMBER	Wet Air Temperature (Stake 2 Top)	CTN
TF07	CHAMBER	Wet Air Temperature (Stake 3 Low)	CTN
TF08	CHAMBER	Wet Air Temperature (Stake 3 Middle)	CTN
TF09	CHAMBER	Wet Air Temperature (Stake 3 Top)	CTN
TF10	CHAMBER	Wet Air Temperature (Stake 4 Low)	CTN
TF11	CHAMBER	Wet Air Temperature (Stake 4 Middle)	CTN
TF12	CHAMBER	Wet Air Temperature (Stake 4 Top)	CTN
TF13	CHAMBER	Wet Air Temperature (Stake 5 Low)	CTN
TF14	CHAMBER	Wet Air Temperature (Stake 5 Middle)	CTN
TF15	CHAMBER	Wet Air Temperature (Stake 5 Top)	CTN
TF16	CHAMBER	Dry Air Temperature (Stake 1 Low)	CTN
TF17	CHAMBER	Dry Air Temperature (Stake 1 Middle)	CTN
TF18	CHAMBER	Dry Air Temperature (Stake 1 Top)	CTN
TF19	CHAMBER	Dry Air Temperature (Stake 2 Low)	CTN
TF20	CHAMBER	Dry Air Temperature (Stake 2 Middle)	CTN
TF21	CHAMBER	Dry Air Temperature (Stake 2 Top)	CTN
TF22	CHAMBER	Dry Air Temperature (Stake 3 Low)	CTN
TF23	CHAMBER	Dry Air Temperature (Stake 3 Middle)	CTN
TF24	CHAMBER	Dry Air Temperature (Stake 3 Top)	CTN
TF25	CHAMBER	Dry Air Temperature (Stake 4 Low)	CTN
TF26	CHAMBER	Dry Air Temperature (Stake 4 Middle)	CTN
TF27	CHAMBER	Dry Air Temperature (Stake 4 Top)	CTN
TF28	CHAMBER	Dry Air Temperature (Stake 5 Low)	CTN
TF29	CHAMBER	Dry Air Temperature (Stake 5 Middle)	CTN
TF30	CHAMBER	Dry Air Temperature (Stake 5 Top)	CTN
TF31	CHAMBER	Resultant Air Temperature (Stake 1 Low)	CTN
TF32	CHAMBER	Resultant Air Temperature (Stake 1 Middle)	CTN
TF33	CHAMBER	Resultant Air Temperature (Stake 1 Top)	CTN
TF34	CHAMBER	Resultant Air Temperature (Stake 2 Low)	CTN
TF35	CHAMBER	Resultant Air Temperature (Stake 2 Middle)	CTN
TF36	CHAMBER	Resultant Air Temperature (Stake 2 Top)	CTN
TF37	CHAMBER	Resultant Air Temperature (Stake 3 Low)	CTN
TF38	CHAMBER	Resultant Air Temperature (Stake 3 Middle)	CTN
TF39	CHAMBER	Resultant Air Temperature (Stake 3 Top)	CTN
TF40	CHAMBER	Resultant Air Temperature (Stake 4 Low)	CTN
TF41	CHAMBER	Resultant Air Temperature (Stake 4 Middle)	CTN
TF42	CHAMBER	Resultant Air Temperature (Stake 4 Top)	CTN
TF43	CHAMBER	Resultant Air Temperature (Stake 5 Low)	CTN
TF44	CHAMBER	Resultant Air Temperature (Stake 5 Middle)	CTN
TF45	CHAMBER	Resultant Air Temperature (Stake 5 Top)	CTN
TF46	CHAMBER	Wall Heat Flux (West)	Thermocouple

TF47	CHAMBER	Wall Heat Flux (Ceiling)	Thermocouple
TF48	CHAMBER	Wall Heat Flux (Floor)	Thermocouple
TF49	CHAMBER	Wall Heat Flux (East)	Thermocouple
TF50	CHAMBER	Wall Heat Flux (South)	Thermocouple
TF51	CHAMBER	Wall Heat Flux (North)	Thermocouple
TF52	CHAMBER	Wall Temperature (West)	CTN
TF53	CHAMBER	Wall Temperature (Ceiling)	CTN
TF54	CHAMBER	Wall Temperature (Floor)	CTN
TF55	CHAMBER	Wall Temperature (East)	CTN
TF56	CHAMBER	Wall Temperature (South)	CTN
TF57	CHAMBER	Wall Temperature (North)	CTN
TRS01	TRANSMISSIOMETERS	Receptor 1 Voltage (Center)	Volt DC
TRS02	TRANSMISSIOMETERS	Receptor 2 Voltage (Bottom Left)	Volt DC
TRS03	TRANSMISSIOMETERS	Receptor 3 Voltage (Top Left)	Volt DC
TRS04	TRANSMISSIOMETERS	Receptor 4 Voltage (Bottom Right)	Volt DC
TRS05	TRANSMISSIOMETERS	Receptor 5 Voltage (Top Right)	Volt DC
TRS06	TRANSMISSIOMETERS	Receptor Alimentation Voltage	Volt DC
TRS07	TRANSMISSIOMETERS	Heater Voltage	Volt DC
TRS08	TRANSMISSIOMETERS	Emiter 1 Voltage (Center)	Volt DC
TRS09	TRANSMISSIOMETERS	Emiter 2 Voltage (Bottom Left)	Volt DC
TRS10	TRANSMISSIOMETERS	Emiter 3 Voltage (Top Left)	Volt DC
TRS11	TRANSMISSIOMETERS	Emiter 4 Voltage (Bottom Right)	Volt DC
TRS12	TRANSMISSIOMETERS	Emiter 5 Voltage (Top Right)	Volt DC
TRS13	TRANSMISSIOMETERS	Emiter 1 Current (Center)	Volt DC
TRS14	TRANSMISSIOMETERS	Emiter 1 Temperature (Center)	CTN
V1	METEO	Visibility	4-20mA

Table of figures