Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition
IMECE2013
November 15-21, 2013, San Diego, California, USA

IMECE2013-63466

CONSTRUCTAL DESIGN FOR EFFICIENCY: THE CASE OF AN ENTROPIC WALL WITH CIRCULATING WATER

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This paper presents an effective analysis on the relation between the changing architecture of a flow system and the maximization of global performance under constraints. An entropic wall with circulating water based on LESP concept has been analyzed. It is a wall with good acclimatizing properties generated by circulating water, which is thermally stabilized by exchanges in the ground. The system has been considered by different levels of complexity. The thermal structure is optimized by considering the system as a sequence of building blocks with assemblies of stepwise larger sizes: an entire wall and the entire building.

The optimal flow network is tree shaped. Different levels of optimization have been performed according to the different scale levels. On an elemental scale is has been optimized the properties of the single elemental block constitutive of the considered wall. On a single wall level, the system has been optimized to optimize internal fluid distribution system, maximizing the thermal uniformity and minimizing the weight of the wall.

The calculation process have been improved enriching the Constructal approach by a novel calculation method which has been defined for introducing more systemic algorithmic calculations at engineering level. This method has been defined as Constructal Design for Efficiency.

NOMENCLATURE

Acronyms

CDE	Constructal Design for Efficiency;
LESP	Low Entropy Structured Panel;
PMV	Predicted Mean Vote Index:
PPD	Predicted Percentage Dissatisfied index;
Z.E.T.Ha.	Zero Energy Temporary Habitation;
Z.E.B.R.A.	Zero Energy consumption Building totally Renewable Addicted;
LESP	Low Exergy Structured Panel;
PMV	Predicted Mean Vote Index;
PPD	Predicted Percentage Dissatisfied index;

Symbols

A	Area [m^2];
H	Internal heat production rate of an occupant per unit area [W/m];
L	modes of energy loss from body [W/m];
M	metabolic rate per unit area, [W/m^2];
Q	Heat [W];
T	Temperature [T];
U	Thermal transmittance [kW/m2 K];
s	Thickness [m]
h	Thermal convection coefficient [W/mK]
λ	Thermal conductivity [W/mK]
α	Thermal adduttance [W/mK]

INTRODUCTION

The Constructal theory [1] is a logical model to approach the description of natural phenomena and the optimization of engineering, logistic and management problems with a hierarchical approach. It is based on the Constructal principle enunciated by Adrian Bejan in 1996 [2]: ''for a finite-size open system to persist in time (to survive) it must evolve in such a

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way that it provides easier and easier access to the currents that flow through it.''

In many papers Adrian Bejan and others has defined a logical flow path constructed by a sequence of blocks from elementary units to large system [3-5]. In those papers, the flow path has described as a sequence of steps that starts with the smallest building block (elemental block) and continued in time with larger building blocks (assemblies or constructs).

The subsystem with the highest internal resistivity (slow flow, diffusions, walking, and high cost) was placed at the elemental block level, filling completely the lowest levels. Elements with successively lower resistivity (fast flow, streams, vehicles, and low cost) have been placed in the larger constructs, where they were used to connect the flow between elemental parts of the system. The geometry of each building block has been optimized using this network approach for its own specific approach.

The authors of this paper aim to introduce into the Constructal design method a novel addition that can improve it potentiality and simplify its applicability in a systemic way. This method based on the Constructal principle aims to produce a theoretical design of a system to reach a precise set of specific mission objectives. It has been defined Constructal Design for Efficiency:

The CDE method requires four different stages:

- a preliminary top-down design process (evaluation of the system in its global relations with external environment) to ensure that the full system has a good configuration for the specified goals;
- the constructal optimization of the elemental components to maximize the system performances;
- a comparison between different configurations, if they exists, identifying the best possible solution for the predefined goals.

This method fits perfectly into the Constructal principle but if focused in preliminary basic RTD activities and uses a top-down approach. It considers the system as whole and tries to reach optimal solution considering the system as a whole integrating all the subsystems that compose the full system.

The method has been applied to the study of the complex thermofluiddynamic of an entropic wall with interior circulating water based on the LESP concept developed in University of Modena and Reggio Emilia.

CDE OPTIMIZATION PROCESS

The expected result of this optimization process is the correct definition of a product, which can be easily industrialized. This necessity forced to an effective application of the Constructal Design for Efficiency method adopting its typical dual cycle process represented in Figure 1.

This method can be summarized in the general description inserted below.

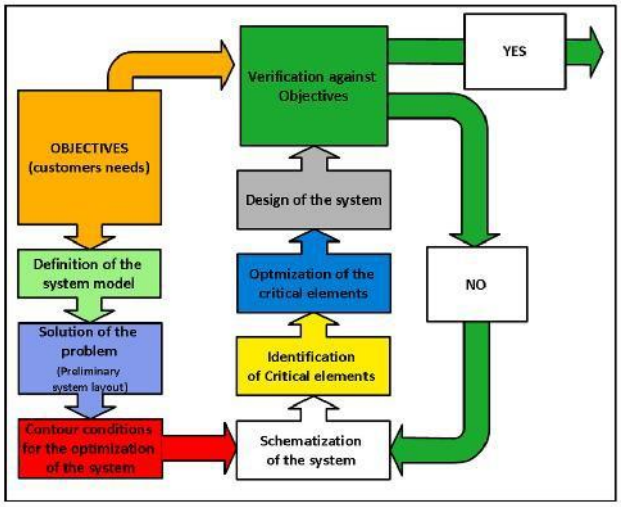


Figure 1. Constructal design for efficiency design method

Top - Down optimization

This process starts from the customer needs and allows defining the contour condition because of the main objective, which needs to be reached by a building realized by the proposed wall. The contour conditions forces to the definition of the preliminary system layout, which allows satisfying better the wellness condition of the potential users.

This preliminary activity is intended to define the system layout for the future constructal optimization process.

Down - Top (constructal) optimization

This is the second necessary step of the CDE process. It is a traditional constructal optimization process, which aims to produce a final design of the system. If the results obtained by the final design reach the original objectives the design is validated, else, if it fails the initial design goals, novel optimization cycles are necessary until when the preliminary goals are satisfied.

THE LESP CONCEPT

The novel feature of this system lies primarily in the renewed approach to the global problem of the building design, which starts from the need to achieve the highest level of comfort while minimizing energy consumption.

The purpose of the LESP system is to create a barrier able to minimize building heat loss and ensure an increased sensation of comfort with the unique contribution of low-level energy, derived from renewable sources. In particular, this wall concept aims maintaining constant the thermo-hygrometric levels of wellness within the building, regardless of external weather conditions, without the need of any energy supply from fossil fuels, and achieving objectives far more ambitious than those associated with the passive house concept. In most cases,

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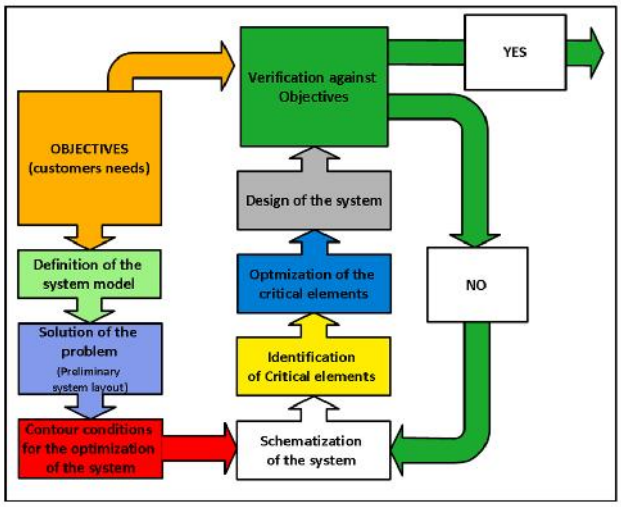


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it does not need any energetic source except the necessary pumping system for the water.

The proposed solution has been studied both using traditional concrete structures [6] and novel polyurethane based container house walls [7,8].

The LESP wall concept is based on a very simple principle shown in Figure 1. In particular, in [8] it has been presented a preliminary ideal model of the wall and the container house.

Figure 2 shows a general schema of the wall with internal piping and Figure 3 shows the thermal behavior of the wall during winter and summer.

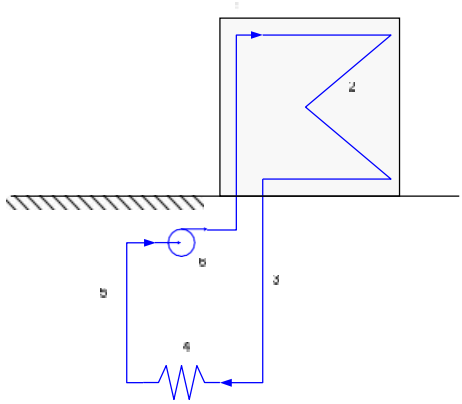


Figure 2. LESP based building schema

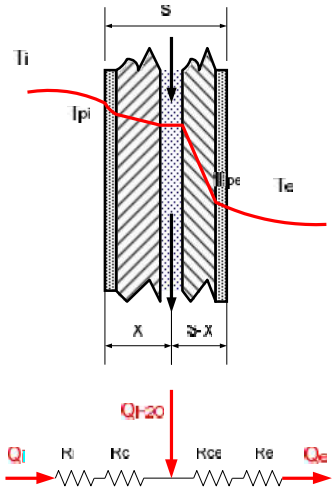


Figure 3. LESP wall schematic concept

Figure 1 presents the schema of the LESP plant The following plant components have been identified:

1) building wall;
2) internal coil for the dynamic insulation of the wall;
3) return pipe;
4) geothermal heat exchanger;
5) discharge pipe;
6) circulation pump.

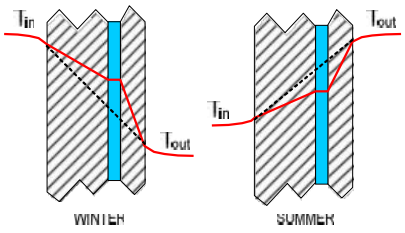


Figure 4 – Seasonal behaviour of the proposed wall.

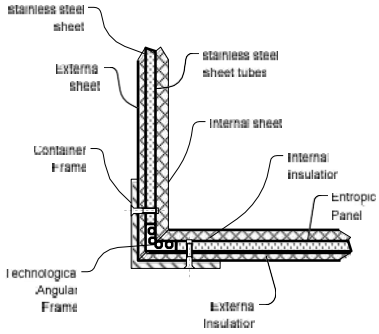


Figure 5. Preliminary LESP structure

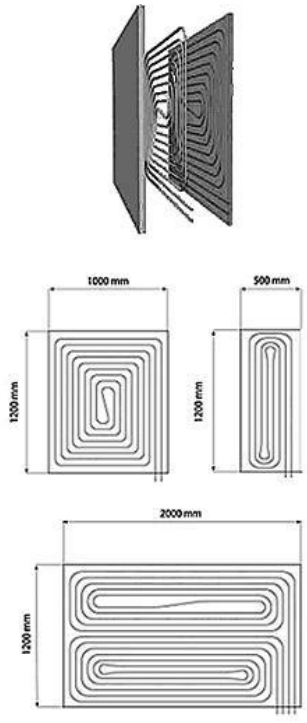


Figure 6. Plasterboard panel and original internal piping design

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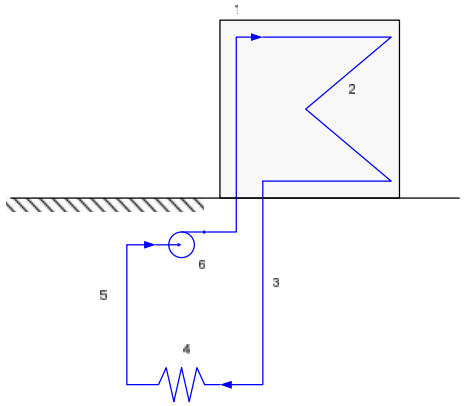


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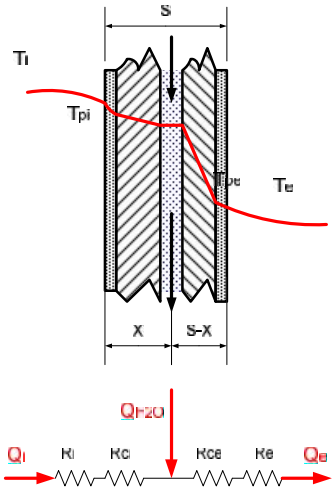


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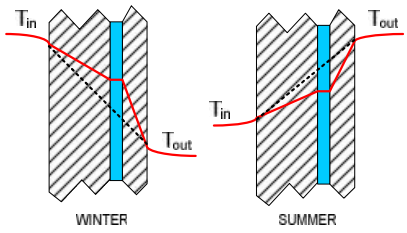


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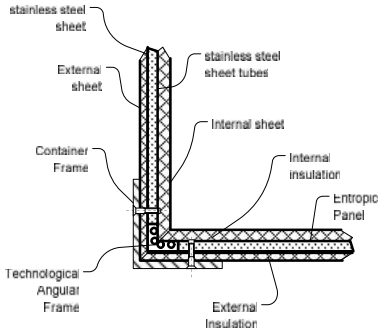


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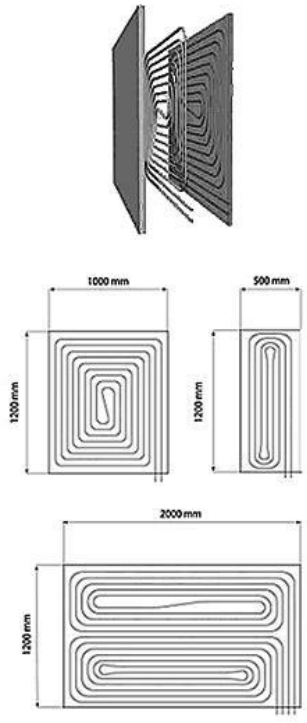


Figure 6. Plasterboard panel and original internal piping design

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CONSIDERATIONS ABOUT DESIGN

The system can be designed properly by some preliminary considerations, which can produce a compromise between static and thermodynamic properties. In precedent papers [15, 16] an internally shielded wall with an internal planar metallic element has been shown (Figure 5). Water distribution elements (Figure 6) inside the wall have been designed using commercial radiant plasterboard panels series, it is possible to consider also a more effective water distribution system.

A better and more stable system can be realized by assuming both a different distribution schema and different architecture of the system, which has lower costs of fabrication.

Some technological considerations about the necessary reduction of costs to ensure an effective system feasibility it has been defined the possibility of introducing successfully into an expanded polyurethane foam wall. In this case, a more effective piping system can be introduced into the wall, combining both structural and thermodynamic properties.

ANALYSIS OF THE PROPOSED WALL STRUCTURE

The preliminary proposed wall structure presents lot of industrial problems. It relates to the cost of the system and of the manufacturing equipments. The system complexity presents a showstopper for system industrialization. It is then necessary to define simpler structures, which allow a large reduction of industrial costs and of provided market prices.

Both plasterboard panels and interior metallic laminates must be eliminated. A possible solution for reduced costs of manufacturing relates to the adoption of a bio-polyurethane wall together with a metallic piping system for water circulation, which guarantees both the thermal shield function and the structural function giving to the resulting system an adequate resistance.

This architecture allows to create the piping inside the polyurethane foam and to define a very simple system and inexpensive manufacturing process.

Economic and production cycle related goals must be fulfilled by an effective satisfaction of traditional needs of the costumers: energy efficiency and interior wellness conditions.

The optimization process will be produced according to the CDE method procedure, which has been widely defined into the introduction of this paper.

OBJECTIVES OF THE DESIGN PROCESS

Two objectives are considered in this paper. They are:

1) Industrial goals: they relates to a fundamental simplification of the industrial process, which leads to the manufacturing of a novel less expensive and more effective version of the proposed wall concept.
2) Energetic goals: they relate to the definition of a wall system, which has the same energy energetic performance of the preliminary design.
3) Customer needs:
    a. aesthetic value;
    b. internal wellness conditions;
    c. reduced costs of internal acclimatization.

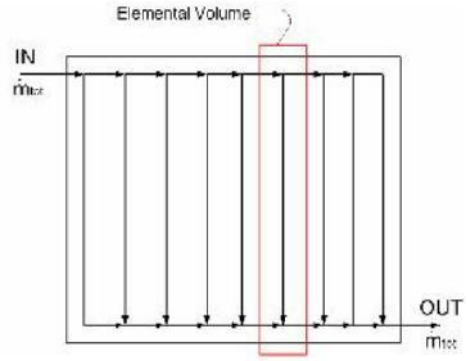


Figure 7. Schema of the wall with identification of the elemental volume

CONCEPTUAL DEFINITION OF THE WALL

Because of preliminary technological considerations, it has formulated the necessity of a novel design of the wall.

The model of the system for calculation has been represented in Figure 7 with the identification of the elemental structure, which will constitute the wall constructal.

The very preliminary schema of the wall represented in Figure 7 shows the novel architecture created by vertical tubes connected by two collectors: one in the upper part of the wall, which distributes the water to the vertical pipes, and one in the lower, which collects the water by the pipes.

In some cases, an external metallic shield can be joined to the pipes connecting them to create an effective thermal shield with much increased thermal uniformity of the system. This possibility must be generally avoided for two reasons:

1) reduction of the industrial costs and of the weight of the wall;
2) simplification of the industrial process for the realizing the walls.

It can be noticed that the piping system without any laminated foil can be placed directly into the envelope, in which the polyurethane foam expands. It has also preferred the vertical pipes architecture because it has an enhanced structural efficiency if compared to the serpentine architecture used in the previous version of the system.

The results of the technologic preventive analysis focused on this pint: the internal metallic pipes can both ensure both the water circulation and produce a fundamental structural contribution to the wall.

This architecture allows considering the wall almost two-dimensional such as in Figure 7. The system is a two-dimensional as in the example shown in Figure 4.

The optimization process aims to reach four different objectives:

1) definition of the optimal thickness of the wall;
2) identification of the optimal positioning of the thermal shield by vertical pipes inside the wall.

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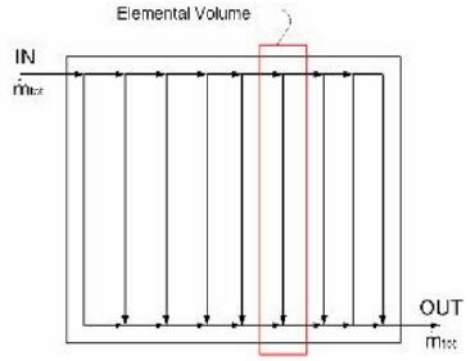


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3) definition of the optimal distance between vertical pipes to ensure a good uniformity of the thermal shield;
4) minimization of the thermal exchange between the interior environment and the thermal shield realized by circulating water

The boundary conditions of the problem can be reduced to the following formulations:

1) wellness internal conditions (PPM about zero);
2) external reference temperatures by Italian and EU standards for the north of Italy [13, 14].

Reference static temperatures for determining the heat transmission of the wall are:

- Internal Reference Temperature:
  - Summer 26 °C;
  - Winter 22 °C;
- External Reference Temperature:
  - Summer 35 °C;
  - Winter -5 °C.

Assuming a location in northern Italy according to schema provided in Figure 2, the average barrier temperature can be assumed equal to the ground water temperature and it has been evaluated about 13.5°C (during winter) and 15°C (during summer).

Materials assumed have reported in Table 3.

Table 1. Material Properties

n.	Material	ρ [kg/m3]	k [W/mK]	α [W/K]	c [J/kg K]
	External adduction			25	
1	Clays External finishing	2300	1		1000
2	Polyurethane	40	0.022		1600
3	Internal finishing	900	0.21		1000
	Internal adduction			7.7	
	Steel piping	8000	17		500

Table 2. Specific Heat Capacity of Ethylene Glycol based Water Solutions

	Specific Heat - cp - [J/(kg K)]						
Temp.	**Ethylene Glycol Solution (% by volume)**						
(°C)	**25**	**30**	**40**	**50**	**60**	**65**	**100**
-40	1)	1)	1)	1)	2847.02	2943.32	1)
-17.8	1)	1)	3475.04	3265.7	3027.06	2930.76	2260.87
4.4	3822.55	3726.25	3537.85	3328.51	3131.73	3018.68	2352.98
26.7	3856.04	3776.49	3600.65	3412.24	3215.46	3110.79	2470.21
48.9	3906.28	3830.92	3663.45	3483.42	3299.2	3202.9	2562.32
71.1	3935.59	3872.79	3726.25	3558.78	3391.31	3290.82	2679.55
93.3	3990.02	3918.84	3789.05	3621.58	3475.04	3378.75	2763.29
115.6	2)	2)	2)	2)	2)	3466.67	2884.71
137.8	2)	2)	2)	2)	2)	2)	2972.63

It can be then assumed to cool the system by an Ethylene Glycol based Water solutions. In Table 2 it has been reported the thermodynamic properties of this kind of solutions with different concentrations.

To avoid possible icing problems during winter a solution with at least 40% Ethylene Glycol can be used. A solution with 50% of Ethylene glycol has been assumed.

In conclusion, it can be affirmed with out any doubt that the objective of the present optimization is related to de design of the industrial product (lightweight polyurethane LESP wall) according to a less expansive architecture than the originally produced design, in order to reach two fundamental goals: excellence in thermal insulation and customer wellness conditions. The verification of the feasibility and the preliminary design of a low cost solution is a fundamental element, necessary for any further development of the project.

OBJECTIVES OF THE DESIGN ACTIVITY

Wellness goals and interior wall temperature.

Internal wellness conditions can be calculated by the evaluation of the internal wellness parameters. Fanger [9] and ASHRAE [10-12] have defined a thermal sensation scale by using PMV, Predicted Mean Vote Index. It allows assessing thermal comfort in an occupied zone based on different physical conditions. PMV values ranges from -3 (cold) to +3 (hot). It can be calculated by equation (1):

$$PMV = \left(0.303 \cdot e^{-0.036M} + 0.028\right) \cdot (H - L) \qquad (1)$$

where H is the internal heat production rate of an occupant per unit area [W/m], L represents the energy loss from body [W/m], M is the metabolic rate per unit area, [W/m^2].

The other fundamental wellness parameter is PPD (Predicted Percentage Dissatisfied index) which considers that at least 5% of people in a group will be dissatisfied with the thermal climate - even with PMV = 0. PPD is calculated by the following expression:

$$PPD = 100 - 95 \cdot e^{\left(-0{,}03353 \cdot PMV^4 - 0.2179 \cdot PMV^2\right)} \qquad (2)$$

The main objective is relative to have an adequate comfort condition inside the building reported in Table 1.

Table 3. Wellness conditions goals

Parameter	Objectives
PMV	0.0
PPD	5.0

The parameters reported in Table 3 have been imposed during winter. A possible combination of the parameters, which allows reaching the above goals, has presented in Table 4.

Thermal exchange related Goals

The second set of design objectives is related to the energy exchange process. The design solution can ensure two fundamental goals:

1) The thermal dispersion of the system must be very low also in comparison with most energetically efficient walls which

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3) definition of the optimal distance between vertical pipes to ensure a good uniformity of the thermal shield;
4) minimization of the thermal exchange between the interior environment and the thermal shield realized by circulating water

The boundary conditions of the problem can be reduced to the following formulations:

1) wellness internal conditions (PPM about zero);
2) external reference temperatures by Italian and EU standards for the north of Italy [13, 14].

Reference static temperatures for determining the heat transmission of the wall are:

- Internal Reference Temperature:
  - Summer 26 °C;
  - Winter 22 °C;
- External Reference Temperature:
  - Summer 35 °C;
  - Winter -5 °C.

Assuming a location in northern Italy according to schema provided in Figure 2, the average barrier temperature can be assumed equal to the ground water temperature and it has been evaluated about 13.5°C (during winter) and 15°C (during summer).

Materials assumed have reported in Table 3.

Table 1. Material Properties

n.	Material	ρ [kg/m3]	k [W/mK]	α [W/K]	c [J/kg K]
	External adduction			25	
1	Clays External finishing	2300	1		1000
2	Polyurethane	40	0.022		1600
3	Internal finishing	900	0.21		1000
	Internal adduction			7.7	
	Steel piping	8000	17		500

Table 2. Specific Heat Capacity of Ethylene Glycol based Water Solutions

	Specific Heat - cp - [J/(kg K)]						
Temp.	**Ethylene Glycol Solution (% by volume)**						
(°C)	**25**	**30**	**40**	**50**	**60**	**65**	**100**
-40	1)	1)	1)	1)	2847.02	2943.32	1)
-17.8	1)	1)	3475.04	3265.7	3027.06	2930.76	2260.87
4.4	3822.55	3726.25	3537.85	3328.51	3131.73	3018.68	2352.98
26.7	3856.04	3776.49	3600.65	3412.24	3215.46	3110.79	2470.21
48.9	3906.28	3830.92	3663.45	3483.42	3299.2	3202.9	2562.32
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1) The thermal dispersion of the system must be very low also in comparison with most energetically efficient walls which

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could be realized today (a thermal dispersion of *1.2 W/m²* has assumed).

2) even if no metallic laminate is used, it is necessary to have a good degree of uniformity of the wall thermal uniformity of the wall.
3) the thermal dispersion of the system must ensure a maximum thermal dissipation of *1.2 W/m²*.

DEFINITION OF THE SYSTEM MODEL

An initial approximation of the wall assumes the interior barrier as a uniform one. The model for calculation has represented in Figure 4, with the identification of the elemental structure, which will constitute the wall constructal.

During winter, the system is heated by a constant heat flux q_{in}. It is equal to the average heat flux dispersed from the interior q_{at} to the external environment. In the summer, the thermal fluxes are inverted. A constant mass flow of water m at uniform inlet temperature equal to the groundwater temperature in the considered location stabilizes the temperature inside the wall.

Table 4. A possible set of parameters that allows reaching the wellness conditions

Parameter	Input
Clothing (clo)	1
Air temp. (°C)	22
Mean radiant temp.	21
Activity (met)	1.2
Air speed (m/s)	0.1
Relative humidity (%)	50



Figure 8. LESP wall schema

Elemental model can be described as a composite wall. Thermal resistances

$$R = \frac{\Delta T}{q} \qquad (3)$$

add, like electrical resistances ($R=V/I$) in series $R=\Sigma_i R_i$. Heat flows across planar layers of thickness s_i and conductivity k_i and the thermal resistance is:

$$R_j = \frac{1}{h_{in}} + \sum_i \frac{s_i}{k_i} + \frac{1}{h_{out}} \qquad (4)$$

Assuming equations 3 and 4, the system can be modeled by the following final model:

$$q_{in,b} = \frac{\Delta T_{in,b}}{R_{in}}; \quad q_{b,out} = \frac{\Delta T_{b,out}}{R_{out}} \qquad (5)$$

$$q_{inb} + q_{b} = q_{bout} \qquad (5)$$

The main problem of system modeling relates to the positioning of the thermal barrier.

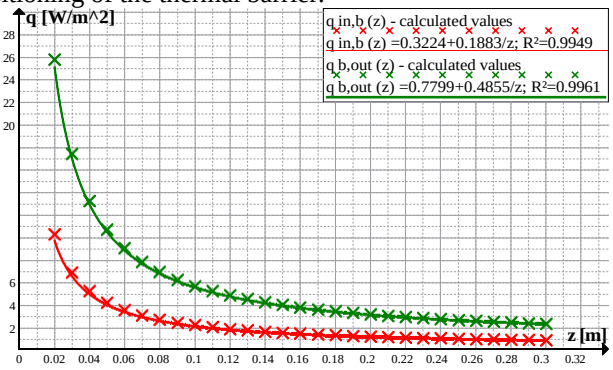


Figure 9. Heat fluxes from interior temperature to thermal barrier and from interior barrier to exterior temperature (Winter case).

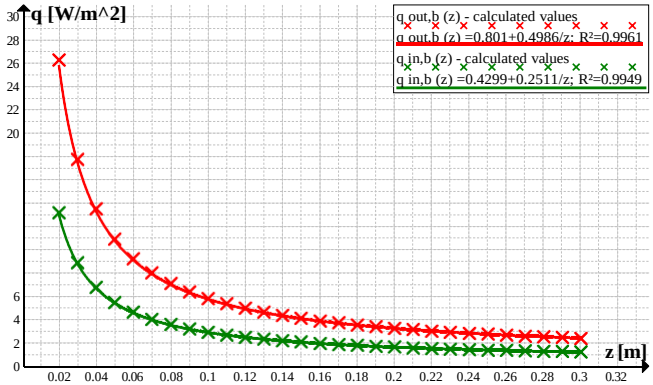


Figure 10. Heat fluxes from exterior temperature to thermal barrier and from interior temperature to barrier (Summer case).

It has been calculated the heat fluxes for different internal and external walls assuming the reference conditions defined. The graphs have been plotted in figures 9 and 10 together with interpolating functions.

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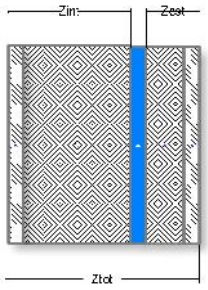


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Assuming equations 3 and 4, the system can be modeled by the following final model:

$$\dot{q}_{in,b} = \frac{\Delta T_{in,b}}{R_{in}}; \quad \dot{q}_{b,out} = \frac{\Delta T_{b,out}}{R_{out}} \qquad (5)$$

$$\dot{q}_{in,b} + \dot{q}_b = \dot{q}_{b,out} \quad (5)$$

The main problem of system modeling relates to the positioning of the thermal barrier.

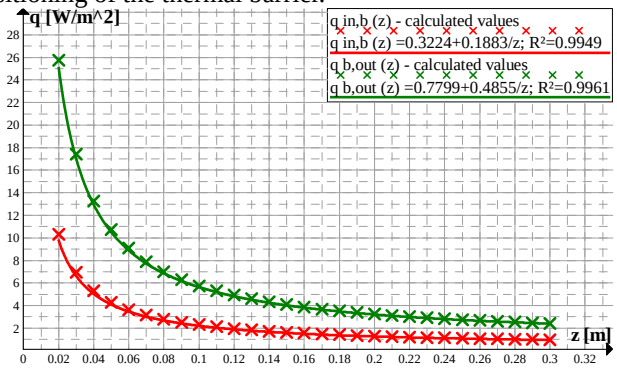


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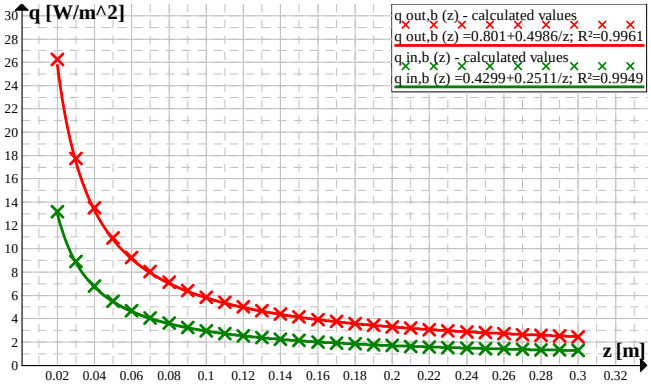


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