# Constructal Design of an Entropic Wall With Circulating Water Inside

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# Constructal Design of an Entropic Wall With Circulating Water Inside

*An entropic wall with circulating water inside could be a solution for acclimatizing a new building with high-energy efficiency and high levels of internal comfort. If circulating water is thermally stabilized by exchanging in the ground such has it happens in geothermal plants, a thermal shield could be realized keeping walls in comfort conditions and minimizing energy needs for further temperature regulations. This paper presents optimization guidelines of such a wall with the objective of maximizing the performances of the wall for reaching optimal internal wellness conditions. Optimization has been realized by a constructal law based method, which has been personalized by a step-by-step process and has been named constructal design for efficiency (CDE). The optimization of the system has been produced at different levels. It starts from a preliminary analysis at system levels, which allow defining the best objectives that could be reached. After this preliminary process, the system has been divided into modules, and the critical ones which have higher influence on the performances of the system have been evaluated. This analysis has been coupled also with an industrial analysis with the goal of defining an effective layout, which could be also manufactured with acceptable costs. The result has produced a final solution with a very good compromise between energetic performances and minimization of costs at industrial level. The results open interesting perspectives for the constructal law to become the core of an effective methodology of an industrial design which can couple perfectly with the modular approach which is currently the major part of industrial companies.* [DOI: 10.1115/1.4033346]

## Introduction

**Low Entropy Structured Panel (LESP) Concept.** The LESP wall concept has been defined by Dumas and coworkers [1]. It is a wall with an internal thermal cut, in which water flows and has been thermally stabilized exchanging heat in the soil, such as in a geothermal plant. The water, which circulates inside the LESP system, creates a thermal barrier with evident benefits on the building.

(1) It uses a low-temperature renewable energy source (the ground below the building).
(2) It reduces the heat exchange through the wall both in summer and winter conditions.
(3) It increases wellness conditions reducing the radiative components of discomfort.

If correctly dimensioned, it could be possible to reduce consistently the thermal flux, which is dispersed by the internal part of the building and to maintain almost constant the thermohygrometric levels of wellness within the building, regardless of external weather conditions, with or without reduced need of energy supply from fossil fuels, and achieving objectives which are far more ambitious than those associated with the passive house concept. In most cases, 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 [2] and for the adoption in container housing [3,4]. How LESP works is presented in Fig. 1. In particular, Dumas et al. [4] produced a preliminary industrial grade configuration of the wall and the container house. Figure 1 shows a general schema of the LESP system, Fig. 2 presents the thermal exchange schema, and Fig. 3 shows the thermal behavior of the wall during winter and summer.

Figure 1 presents the schema of the LESP plant. The following components can be identified:

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

The design activity requires a compromise between structural and heat transfer properties. Precedent evaluations have defined a preliminary architecture [3,4] by the simultaneous use of a

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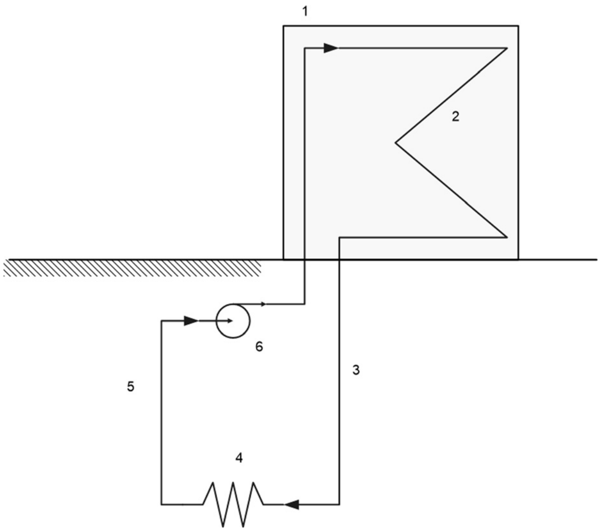

Fig. 1 LESP-based building and plant schema

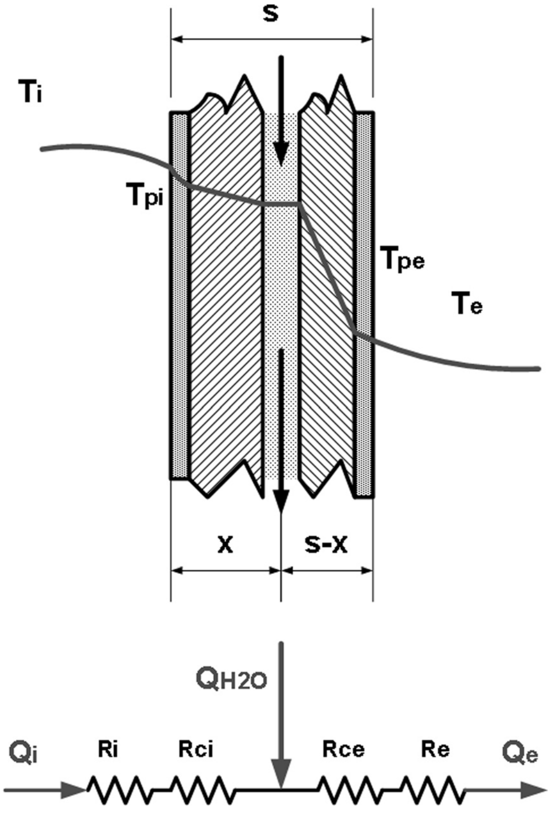

Fig. 2 LESP wall schematic concept

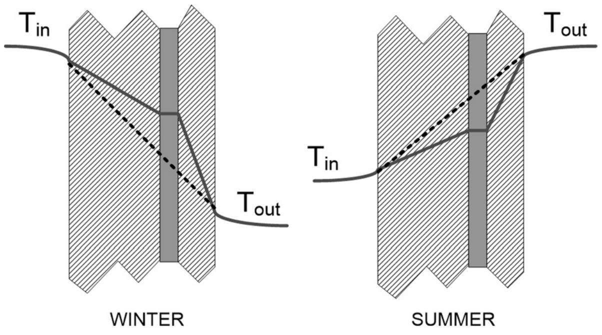

Fig. 3 Seasonal behavior of the proposed wall

metallic laminate and an element for water circulation created by radiant plasterboard panels. Even if this solution works excellently, it still presents too high costs for materials and manufacturing, which generates a market price that is not acceptable for the market. On the other side, any increase and a further optimization in terms of thermal distribution is possible by a more accurate optimization.

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

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

**Optimization Method.** Constructal theory [5] 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 [6]: "for a finite-size open system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it."

Bejan and coworkers have defined a logical flow path constructed by a sequence of blocks from elementary units to a large system [7–9]. In those papers, the flow path has been 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 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.

This uses a new design approach, which is still under definition, and has been defined CDE. It has been defined by Trancossi and coworkers [10,11] for the optimization of airships with energy self-sufficiency. It aims at producing a theoretical design method based on a precise set of specific mission objectives [12,13] and based on the constructal law. This method has been defined CDE. It is structured in four different stages:

(1) a preliminary top-down design process (evaluation of the system in its global relations with external environment) to define a preliminary layout for the specified goals of the design process
(2) the constructal optimization of the elemental components of the system which aims to maximize the system performances
(3) definition of possible alternative configurations and comparison, if they exist, to identify the better solution for the predefined goals
(4) analysis against existing technologies allows defining final design against technology readiness levels of the possible components

The method has been applied to the study of the complex thermofluidodynamic of an entropic wall with interior circulating water based on the LESP concept. Objectives relate to both optimization of the performances of a physical system and definition of a solution, which can be industrialized, taking into account also a set of objectives that takes into account also manufacturing-related and cost-related objectives in order to demonstrate the possibility of introduction into the market.

The design of a new industrial product requires the demonstration of its performances and its economic potential. It means that a new product has to satisfy multiple conditions [14–18]:

(1) *Increase of technical performances*: They require understanding level of innovation, which is generated by the innovation, with respect to the actual offer.
(2) *Reduction of prices and costs of utilization for the customers*: Their evaluation is necessary to verify if the proposed innovation could be acceptable for the customers.
(3) *Industrial costs and economic performances*: It is necessary to understand if production and installation costs are acceptable in relation to the market and of how they ensure a future perspective vision for the company.
(4) *Minimization of LCA impacts*: Reduction of the environmental imprint of the product design with an accurate evaluation of production, operative life, and end of life environmental impacts.

Figure 4 presents a schema of this evaluation process, which must necessarily take into account all the dimensions of the necessary optimization process that is required at industrial level to verify the effective feasibility of an industrial product and of its possible market introduction. The expected result of this optimization process is the correct definition of a product, which can be easily industrialized.

**Discussion About the Adopted Method.** Constructal theory is controversial inside the scientific community. A multiobjective optimization is produced according to constructal law and laws of thermodynamic. Constructal law can explain many natural phenomena and their evolution [19–30].

At industrial design level, it could ensure an effective planning of both the development directions and increase of performance of a system over time. It then allows defining a design that can evolve over time increasing its own performance by successive steps. Focusing on this important goal, the authors have started an analysis process by solving possible problems keeping in mind a potential industrial perspective and by analyzing cases with different complexities.

Milestone reference about the specific problem has been produced by Bejan's analysis of T-shaped fins [31] and Zanfirescu [32], who have studied and optimized a tree-shaped cooling plate for an ice-skating plant. Ding and Yamazaki [33] evolved this research direction by approaching constructal design of cooling channel in heat transfer system by utilizing optimality of branch systems in nature. Zimparov et al. [34] defined an effective guideline for the optimization of tree-shaped flow geometries with constant channel wall temperature.

Rocha et al. [35] approached the geometric optimization of shapes of heat exchange systems based on constructal theory. Moreno and Tao [36] studied thermal and flow performance of a microconvective heat sinks with three-dimensional constructal channel configuration leading to a robust modeling of heat sinks.

Even if specifically relating to the design of finned modules, Zhang and Liu [37] defined the guidelines for an optimum geometric arrangement of vertical rectangular fin arrays in natural convection. Lorenzini and Moretti [38] proposed an important model of heat exchanging finned modules with air in forced convection and laminar flow condition. Otherwise, different conditions have been considered, Lorenzini's activity has a large methodological importance on this research. Lorenzini and Moretti [39] also produced a robust constructal theory based analysis of gas–liquid cooled finned modules.

Hajmohammadi et al. [40] improved forced convection model by considering the attachment of heat sources to a conducting thick plate. This work will be the key reference for the future activities, which relates to coupling the LESP concept with a photovoltaic electric production. Hajmohammadi et al. [41] also produced a conjugate analysis of the effects of a thick plate on the excess temperature of iso-heat flux heat sources cooled by laminar forced convection flow. The analysis of cavities and their modeling have also a fundamental importance on this research activity. In this field, it is necessary to cite the fundamental study by Rocha et al. [42], which is the base for research activities in this field. Hajmohammadi et al. [43] reconsidered the constructal design of cavities and introduced for the first time manufacturing-related considerations, which have a particular importance for the present research, which aims to produce not the best-ever theoretical solution to a physical problem, but introduces the exigency of designing an industrial product which could be realized and introduced into the market. Lorenzini et al. [44] considered constructal design of convective Y-shaped cavities by means of genetic algorithms. Lorenzini et al. [45] also studied the constructal design of convective cavities inserted into a cylindrical solid body for cooling processes.

**Guidelines of Design and Optimization Process.** The preliminary proposed LESP wall structure, which has been studied [1–5], presents adequate performances [5] but presents industrial problems both related to the costs for materials and for manufacturing. Such problems relate to the costs of the system and of manufacturing processes introducing a potential showstopper for system industrialization. It is then necessary to define a simpler and costless system architecture, which allows a large reduction of industrial costs and 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 biopolyurethane wall together with a metallic piping system for

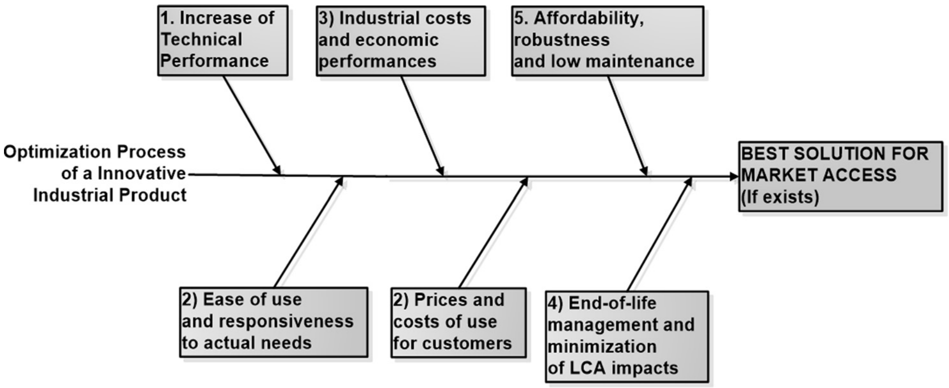

**Fig. 4 Schema of the necessary multiobjective and multidisciplinary optimization process, which is performed at industrial level**

water circulation, which guarantees both the thermal shield function and the structural function giving the resulting system an adequate resistance. This architecture of the wall allows to create the piping inside the polyurethane foam and to define a simple system with lower manufacturing costs. The model for this activity has been defined according to Zamfirescu and Bejan, [32], Ding and Yamazaki [33], and Miguel [46]. The goals of the present research activity are then focused on the design of an industrial ready product, which could meet the need of increasing the wellness conditions inside the building. The optimization process will be produced by coupling traditional constructal optimization with the CDE method procedure [11–14].

In particular, the following set of goals is considered:

(1) Industrial goals: They relate 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:
    - esthetic value
    - internal wellness conditions
    - reduced costs of internal acclimatization

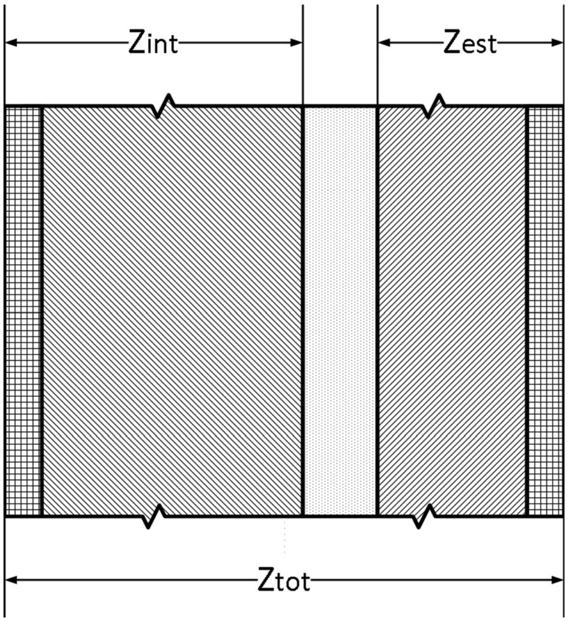

Fig. 6 LESP wall schema

## Conceptual Definition of the LESP Wall

**LESP Wall Layout.** The preliminary schema of the wall is represented in Fig. 5, which 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. Figure 5 allows also the identification of the elemental structure that constitutes the constructal. 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 even if interesting causes an increment in terms of costs because of two main reasons:

- reduction of the industrial costs and the weight of the wall
- simplification of the industrial process for 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 versions of the system [1–4].

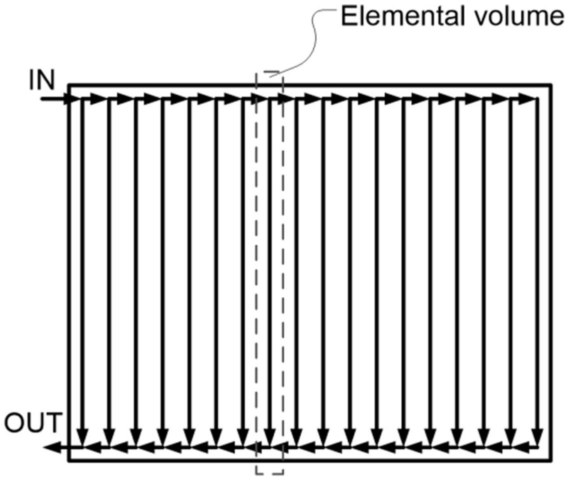

Fig. 5 Schema of the wall with identification of the elemental volume

The results of the technologic preventive analysis focused on a precise point: the internal metallic pipes can 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 Fig. 6. The cross section is almost two-dimensional as in the example shown in Figs. 2 and 3.

**Setup of the Optimization Process.** The optimization process aims to reach four different technical 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
(3) determination of the distance between vertical pipes to ensure best uniformity of the thermal shield
(4) minimization of the thermal exchange between the interior environment and the thermal shield realized by circulating water

Moreover, to verify two main industrial necessary conditions:

(1) easy and low-cost manufacturability, including limited LCA impacts
(2) price of the LESP wall and its installation that could allow an effective market introduction

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

(1) wellness internal conditions (PPM about zero)
(2) internal and external reference temperatures by Italian and EU standards for the north of Italy [46,47]:
    - internal reference temperature: Summer 26 °C and winter 22 °C
    - external reference temperature: Summer 35 °C and winter −5 °C

Assuming a location in northern Italy according to schema provided in Fig. 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).

**Table 1 Properties of materials**

| No. | Material | $\rho$ (kg/m$^3$) | $K$ (W/m K) | $\alpha$ (W/K) | $c$ (J/kg K) |
| --- | --- | --- | --- | --- | --- |
| 1 | External adduction | | | 25 | |
| 2 | Clays external finishing | 2300 | 1 | | 1000 |
| 3 | Polyurethane | 40 | 0.022 | | 1600 |
| 4 | Internal finishing | 900 | 0.21 | | 1000 |
| 5 | Internal adduction | | | 7.7 | |
| 6 | Steel piping | 8000 | 17 | | 500 |

Materials assumed have been reported in Table 1 according to Norton and Christensen [47] and Feist [48].

It can be then assumed that the circulating fluid is an ethylene glycol based water solution. In Table 2, it has been reported the thermodynamic properties of this kind of solutions with different concentrations according to the manual by The Dow Chemical Company [49].

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 without any doubt that the objective of the present optimization is related to the 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. These technical objectives must be necessarily coupled with an analysis and verification of the feasibility and the preliminary design of a low-cost solution, which is a necessary element for any further development of the project.

**Internal Wellness Conditions.** Internal wellness conditions can be calculated by the evaluation of the internal wellness parameters. Fanger [50] and ASHRAE [51,52] have defined a thermal sensation scale by using predicted mean vote (PMV) index. It allows assessing thermal comfort in an occupied zone based on different physical conditions. PMV values range from −3 (cold) to +3 (hot). It can be calculated by the following equation:

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

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), and $M$ is the metabolic rate per unit area (W/m$^2$).

The other fundamental wellness parameter is predicted percentage dissatisfied (PPD) 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:

$$\mathrm{PPD} = 100 - 95 \cdot e^{(-0.03353 \cdot \mathrm{PMV}^4 - 0.2179 \cdot \mathrm{PMV}^2)} \qquad (2)$$

**Table 3 Wellness conditions goals**

| Parameter | Objectives |
| --- | --- |
| PMV | 0.0 |
| PPD | 5.0 |

**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. (°C) | 21 |
| Activity (met) | 1.2 |
| Air speed (m/s) | 0.1 |
| Relative humidity (%) | 50 |

The main objective relates to adequate comfort conditions inside the building that is described by Indraganti and Daryani Rao [53] and reported in Table 3. The parameters reported in Table 3 have been imposed during winter. A possible combination of the parameters, which allows reaching the above goals, is presented in Table 4.

## Preliminary Top-Down System Model

The classification of the final building in the passive house class requires that the thermal dispersions of the system must be very low also in comparison with the most energetically efficient walls, which could be realized today (a thermal dispersion of 1.2 W/m$^2$ has assumed). It is also necessary that even if no metallic laminate is used, it is necessary to have a good degree of thermal uniformity of the wall.

A preliminary 2D model of the wall can be produced by assuming that the interior barrier has uniform temperature. The model for calculation has been represented in Fig. 4 and is based on a 2D simplification of the elemental structure. In winter conditions, the system is heated by a constant heat flux $\dot{q}_{\mathrm{in}}$. It is equal to the average heat flux dispersed from the interior $\dot{q}_{\mathrm{out}}$ to the external environment. In the summer, the thermal fluxes are inverted. A

**Table 2 Specific heat capacity of ethylene glycol based water solutions**

| | Specific heat, $c_p$ (J/kg K) | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | Ethylene glycol solution (% by volume) | | | | | | |
| Temp. (°C) | 25 | 30 | 40 | 50 | 60 | 65 | 100 |
| −40 | [a] | [a] | [a] | [a] | 2847.02 | 2943.32 | [a] |
| −17.8 | [a] | [a] | 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 | [b] | [b] | [b] | [b] | [b] | 3466.67 | 2884.71 |
| 137.8 | [b] | [b] | [b] | [b] | [b] | [b] | 2972.63 |

[a] Below point of solidification.

[b] Boiling risk conditions.

constant mass flow of water $\dot{m}$ at uniform inlet temperature equal to the groundwater temperature in the considered location stabilizes the temperature inside the wall. By this analysis, it is expected to obtain an effective optimal positioning of the barrier inside the wall section.

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

$$R = \frac{\Delta T}{\dot{q}} \tag{3}$$

are added, such as 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

$$R_j = \frac{1}{h_{\text{in}}} + \sum_i \frac{s_i}{k_i} + \frac{1}{h_{\text{out}}} \tag{4}$$

Assuming Eqs. (3) and (4), the system can be modeled by the following final model:

$$\dot{q}_{\text{in},b} = \frac{\Delta T_{\text{in},b}}{R_{\text{in}}}; \quad \dot{q}_{b,\text{out}} = \frac{\Delta T_{b,\text{out}}}{R_{\text{out}}} \tag{5}$$

$$\dot{q}_{\text{in},b} + \dot{q}_b = \dot{q}_{b,\text{out}} \tag{6}$$

The main problem of system modeling relates to the positioning of the thermal barrier. It is possible to evaluate summer and winter heat exchanges for different internal and external walls assuming that the reference conditions are defined. The graphs have been plotted in Figs. 7 and 8 together with interpolating functions.

The data series in Figs. 7 and 8 have been calculated by Z88 finite elements open source code and verified by ACCASOFT TERMUS-G (a freeware code for thermal characterization of building structures which has been certified according to Italian standards [47,54]). It can be also analyzed the percent energy gain with an LESP wall and a corresponding thickness traditional wall exchanging with the exterior environment (Fig. 9). The obtained functions have a fundamental importance for the transversal positioning of the heat barrier by circulating water inside the wall. An effective optimization of the system for the specific design can be performed assuming the water temperature equal to the groundwater temperature. The specific optimization has been then realized in winter conditions.

The optimization of the system can be performed initially with the aim of placing an effective uniform temperature barrier in the wall. The heat flux from the barrier to the exterior environment can be easily evaluated and is plotted in Fig. 10. The energetic evaluation has preliminary assumed for square mater of wall. The amount of heat transferred to circulating fluid can be expressed by

$$\dot{q} = \dot{m}_{\text{water}} \cdot c_p \cdot \Delta T \tag{6}$$

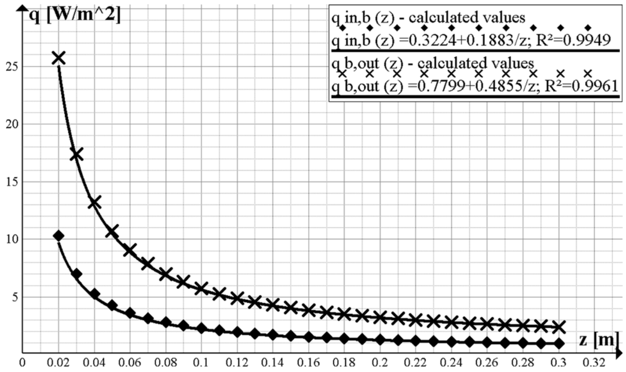

**Fig. 7** Heat fluxes from interior temperature to thermal barrier and from interior barrier to exterior temperature (winter case)

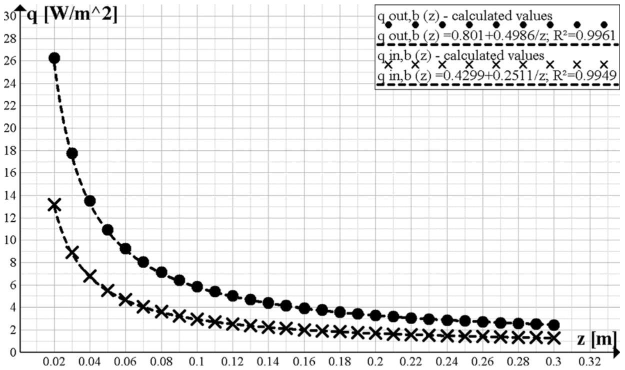

**Fig. 8** Heat fluxes from exterior temperature to thermal barrier and from interior temperature to barrier (summer case)

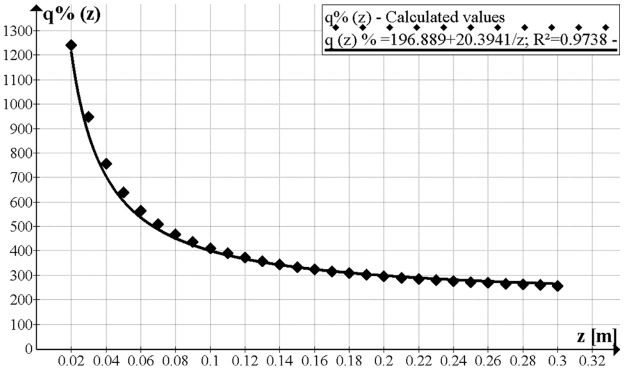

**Fig. 9** Difference of heat dissipation (%) between traditional wall and LESP wall (winter)

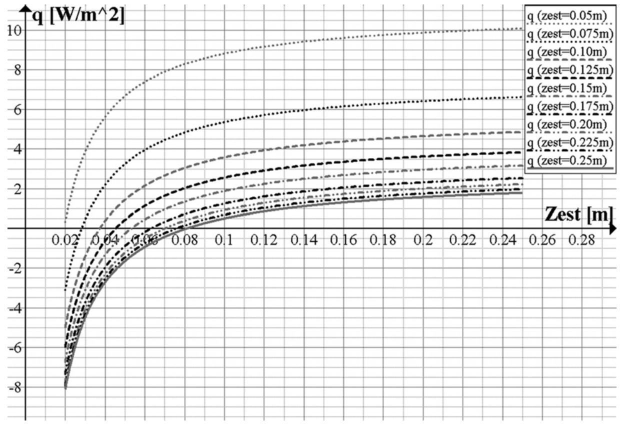

**Fig. 10** Heat dispersed from the barrier to the external environment for different wall thicknesses

Equation (6) allows calculating the mass flow of ethylene glycol based water solution. Assuming any desired internal heat dispersion value, the optimization of the wall can be performed. For example, assuming that heat dispersion in winter conditions is about 1.2 W/m$^2$, the optimal wall geometry can be calculated. Looking at Figs. 8 and 9, an internal wall thickness of 0.2 m can be obtained.

For this value of thickness, the average mass flux from the interior to the pipes can be calculated

$$\dot{q}_{\text{int}} = 1.17\ \text{W/m}^2$$

Consequently, the mass flow can be evaluated as a function of external thickness

$$\dot{m}_{\text{water}} = \frac{\dot{q}}{c_p \cdot \Delta T} \tag{7}$$

which has been plotted in Fig. 11, assuming that the water temperature is almost constant ($\Delta T \cong 0.25\,^{\circ}\mathrm{C}$).

## Bottom-Up Optimization

**Technological and Manufacturing Considerations.** All the necessary data for longitudinal positioning of the thermal barrier have been calculated. It is then necessary to verify the optimized solution for production and costs.

Two possible architectures can be adopted:

(1) an internal rack of vertical pipes
(2) an internal honeycomb panel

They have been both analyzed and preliminarily designed both in industrial and thermal point of view. They are represented in Figs. 12 and 13, respectively.

The productive process and the foaming setups have been analyzed, and the schematic representations have been represented in Fig. 14.

The planar honeycomb extruded appears much simpler in terms of both simpler industrial production process setup and avoidance of thermal discontinuities between pipes. Another difference regards the fact is that no junction between pipes is necessary, avoiding times for accurate positioning and linking of tubes. The honeycomb panel based architecture presents then clear advantages on both an economic and thermal point of view. The price of honeycomb panels is much lower than the one of the tube rack both in terms of material and in terms of times for the production process.

**Further Technological Considerations.** The rack of pipes architecture is necessary in the case of concrete manufactured panels, because of the very high pressures, which applies during the manufacturing process and the necessity of realizing the adhesion conditions between cement and pipes inside the wall system. This architecture has been already analyzed by Madonia et al. [1].

In particular, considering honeycomb-based solutions, different possibilities and solutions can be investigated. Honeycomb panels are produced in different materials raging from plastics such as PET and polycarbonate to metals such as aluminum alloys and iron. This possibility allows the design of multiple solutions depending on specific needs.

The above considerations in terms of both manufacturability and multiplicity of solution encourage the adoption of honeycomb panels instead of racks of pipes solutions.

**Final Heat Exchange Optimization.** A market analysis allows identifying several honeycomb panels with vertical canalizations

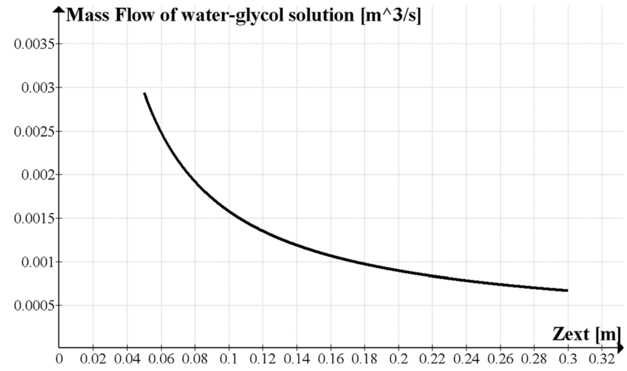

**Fig. 11 Mass flow of water/glycol solution necessary to reach the predefined goals**

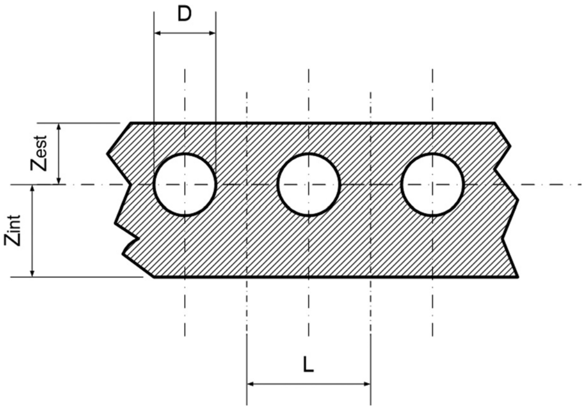

**Fig. 12 Rack of pipes transversal section**

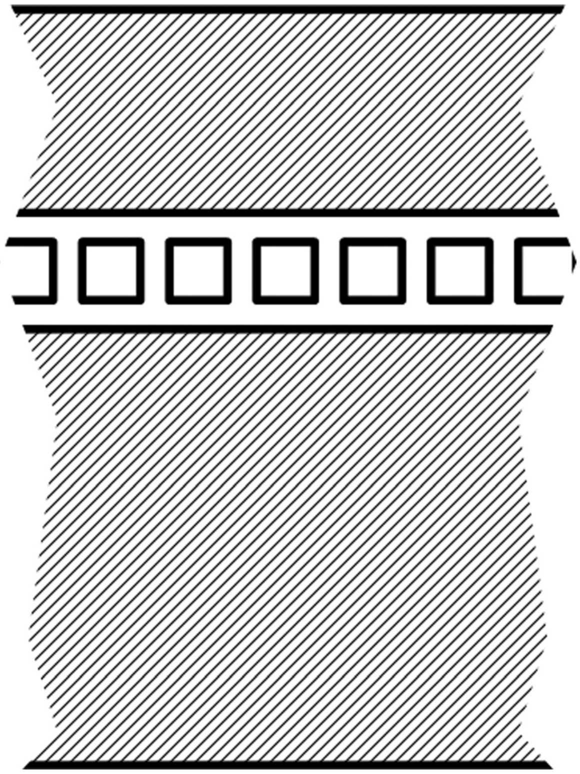

**Fig. 13 Honeycomb extruded panel insertion transversal section**

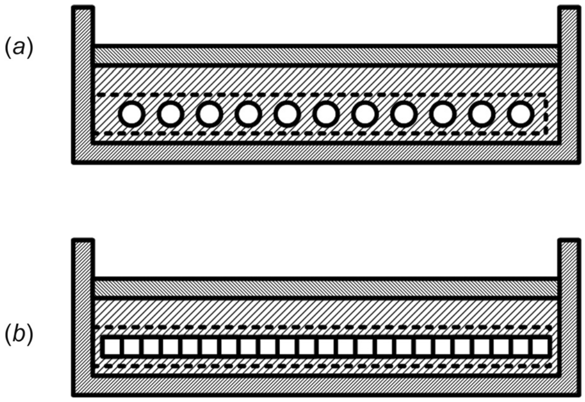

**Fig. 14 Foaming setup schematic representation: (*a*) rack of pipes and (*b*) honeycomb panel**

in different. These panels present a section very similar to the one presented in Fig. 15.

These panels present acceptable mechanical properties and interesting thermal performance. Some can be found in both polycarbonate and aluminum. For structural exigencies, an internal mesh of iron can be applied externally to increase the structural properties of the wall.

A very common polycarbonate profile presents the following dimensions: $x = 10\,\mathrm{mm}$ and $x_{\mathrm{int}} = 6\,\mathrm{mm}$.

Assuming a 50% ethylene glycol based water solution, an effective density of $1066\,\mathrm{kg/m^2}$ can be calculated. Area on internal channels of the honeycomb panel is 36% of panel area, which is 0.01 and channel area is $0.0036\,\mathrm{m^2}$.

It can be defined a resulting heat transfer coefficient for the whole panel. It can be analyzed by Churchill [55,56] and Lloyd and Moran [57].

The required velocity can be calculated for different external thickness values (Fig. 16).

It can be verified that the optimal solution requires reducing the external thickness of the wall while elevated internal thickness of the wall presents large benefits.

It can then optimize the liquid inlet and outlet, which can be defined by constant velocity model. Assuming a constant velocity $u$ inside the system, the section of the inlet and outlet channels can be calculated by considering

$$\dot{m}_{\mathrm{tot}} = \sum_i m_i \text{ and } \dot{m}_{\mathrm{tot},j} = \dot{m}_{\mathrm{tot}} - \sum_j \dot{m}_j$$

the average area of each section is

$$A_{\mathrm{in}} = \frac{\dot{m}_{\mathrm{tot}}}{\rho \cdot u} \text{ and } A_j = \frac{\dot{m}_{\mathrm{tot},j}}{\rho \cdot u} = \frac{\dot{m}_{\mathrm{tot}} - \sum_j \dot{m}_j}{\rho \cdot u}$$

This design method allows evaluating the friction losses and power required by the pump can be easily calculated by Bernoulli theorem.

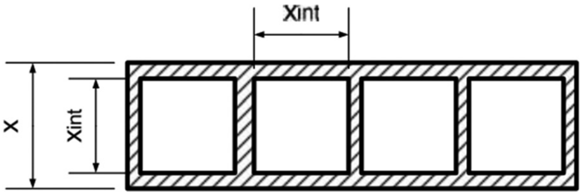

Fig. 15 Honeycomb schema

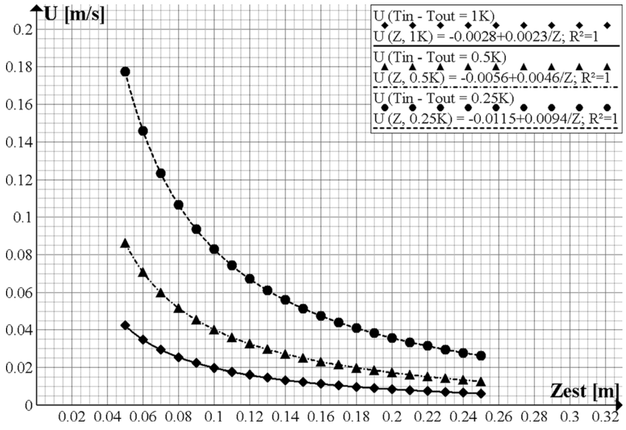

Fig. 16 Required velocity of the ethylene glycol water solution

Assuming 50 mm thickness on the exterior side and $\Delta T_{\mathrm{water}} = 0.25\,^\circ\mathrm{C}$, the pressure loss in any channel can be calculated by Colebrook-White formulation [58]. It can be then calculated the necessary pressure, which has to be granted for a panel with 1 m length and 3 m height. It results less than 65 Pa.

## Conclusions

This paper has presented a sample of application of the constructal principle based optimization focusing on the exigency of synthesizing an innovative industrial product, which has been previously defined. It applies the constructal method by a new formulation which has been defined CDE. It is a process based on two optimization cycles, the first one at full system level defining an ideal solution double cycle design process. The first one at full system level aims to define a preliminary simplified solution, which can be used as a mean of comparison. The second, which considers physical and technological problems and allows an effective bottom-up optimization based on constructal method. The objective of the second step produces, in this case, an effective technological analysis, which aims to discriminate between general system configurations based on their industrial suitability. The obtained configuration is then optimized in order to define a solution that is in line with the preliminary technological choices and allows approximating the preliminary ideal results. It has been also obtained a general dimensioning method for such kind of high-energy efficiency walls. Otherwise, it has been produced a simple solution ready for an easy industrial manufacturing, which can present, if compared to previous designs, lower costs and lighter weights. This obtained architecture will be the basis for further industrial development of the proposed wall with internally circulating water.

In this case, it has been verified that a solution, which allows a very simple manufacturing process, is both industrial and heat transfer related to maximum simplification of the manufacturing process and optimal positioning of the thermal barrier. The mathematic relations which allow producing an effective wall based on the LESP concept has been defined together with the design rules. The obtained system configuration fits perfectly the preliminary defined boundary conditions of the problem.

This result does not validate at this stage the constructal theory as a general physics theory, but claims that constructal law derived design results could produce adequate solutions to industrial design problems. The main advantages of this constructal-based method can be reassumed by three-key points:

(1) It fits industrially adopted modular design methods, which have the merit of the actual increase of robustness of industrial products.
(2) It allows an effective comparison of unknown results by a preliminary, even if simplified, ideal solution stating precisely how far the performances stated into the final configurations are from the ideal one.
(3) It allows an effective optimization of the results and allows generating a number of different configurations that meet the design goals or that could approximate them in an acceptable way, but also allows changing radically the solutions by means of the modification of the technological conditions.

## Nomenclature

$A$ = area ($\mathrm{m^2}$)
CDE = constructal design for efficiency
$H$ = internal heat production rate of an occupant per unit area (W/m)
$H$ = thermal convection coefficient (W/m K)
$L$ = modes of energy loss from body (W/m)
LESP = low entropy structured panel
$M$ = metabolic rate per unit area ($\mathrm{W/m^2}$)

PMV = predicted mean vote index
PPD = predicted percentage dissatisfied index
$Q$ = heat (W)
$S$ = thickness (m)
$T$ = temperature (T)
$U$ = thermal transmittance (kW/m$^2$ K)
Z.E.T.Ha. = zero energy temporary habitation
Z.E.B.R.A. = zero energy consumption building totally renewable addicted
$\alpha$ = thermal exchange (convection and radiation) (W/m K)
$\lambda$ = thermal conductivity (W/m K)

## References

[1] Madonia, M., Dumas, A., and Trancossi, M., 2011, *Studio del Comportamento di due Pannelli a Diversa Tipologia di Taglio Termico*, Convegno Annuale ATI, Rende, Italy.
[2] Dumas, A., Trancossi, M., Madonia, M., Bonnici, M., Scaccaglia, P. B., and Guareschi, M. C., 2012, "A Novel Concept of Container House With Zero Energetic Consumption," SAE Technical Paper No. 2012-01-1507.
[3] Dumas, A., Trancossi, M., Madonia, M., Pirondi, A., Garziera, R., Frizziero, L., and Piancastelli, L., 2012, "Z.E.T.Ha.: Zero Energy Temporary Habitation," ASME Paper No. IMECE2012-87666.
[4] Dumas, A., Trancossi, M., Madonia, M., and Coppola, M., 2014, "Zero Emission Temporary Habitation: A Passive Container House Acclimatized by Geothermal Water," ASME J. Sol. Energy Eng., **136**(4), p. 044505.
[5] Bejan, A., 2000, "Shape and Structure," *Engineering to Nature*, Cambridge University Press, Cambridge, UK.
[6] Bejan, A., 1997, *Advanced Engineering Thermodynamics*, 2nd ed., Wiley, New York.
[7] Bejan, A., and Errera, M. R., 2000, "Convective Trees of Fluid Channels for Volumetric Cooling," Int. J. Heat Mass Transfer, **43**(17), pp. 3105–3118.
[8] Bejan, A., 2002, "Dendritic Constructal Heat Exchanger With Small Scale Cross Flows and Larger-Scales Counter Flows," Int. J. Heat Mass Transfer, **45**(23), pp. 4607–4620.
[9] Bejan, A., and Lorente, S., 2010, "The Constructal Law and the Design of the Biosphere: Nature and Globalization," ASME J. Heat Transfer, **133**(1), p. 011001.
[10] Trancossi, M., Dumas, A., and Madonia, M., 2013, "Optimization of Airships With Constructal Design for Efficiency Method," SAE Technical Paper No. 2013-01-2168.
[11] Dumas, A., Madonia, M., Trancossi, M., and Vucinic, D., 2013, "Propulsion of Photovoltaic Cruiser-Feeder Airships Dimensioning by Constructal Design for Efficiency Method," SAE Int. J. Aerosp., **6**(1), pp. 273–285.
[12] Dumas, A., Trancossi, M., and Madonia, M., 2013, "Morphoplane, Energetic Analysis of a Novel Green Aerial Vehicle Concept," ASME Paper No. ESFuelCell2013-18166.
[13] Dumas, A., Trancossi, M., and Madonia, M., 2012, "Energetic Design and Optimization of a Large Photovoltaic Stratospheric Unconventional Feeder Airship," SAE Int. J. Aerosp., **5**(2), pp. 354–370.
[14] Cooper, R. G., 1979, "Identifying Industrial New Product Successes: Project New Prod," Ind. Mark. Manage., **8**(2), pp. 124–135.
[15] Link, P. L., 1987, "Keys to New Product Success and Failure," Ind. Mark. Manage., **16**(2), pp. 109–118.
[16] Rochford, L., 1991, "Generating and Screening New Product Ideas," Ind. Mark. Manage., **20**(4), pp. 287–296.
[17] Woodruff, R. B., 1997, "Customer Value: The Next Source for Competitive Advantage," J. Acad. Mark. Sci., **25**(2), pp. 139–153.
[18] Hart, S., Hutlink, E. J., Tzokas, N., and Commandeur, H. R., 2003, "Industrial Companies' Evaluation Criteria in New Product Development Gates," J. Prod. Innovation Manage., **20**(1), pp. 22–36.
[19] Bejan, A., and Sciubba, E., 1992, "The Optimal Spacing of Parallel Plates Cooled by Forced Convection," Int. J. Heat Mass Transfer, **35**(12), pp. 3259–3264.
[20] Bejan, A., 2013, "Technology Evolution, From the Constructal Law," *Advances in Heat Transfer*, Vol. 45, E. M. Sparrow, J. P. Abraham, and J. M. Gorman, eds., Academic Press, Burlington, VT, pp. 183–207.
[21] Kobayashi, H., Lorente, S., Anderson, R., and Bejan, A., 2012, "Freely Morphing Tree Structures in a Conducting Body," Int. J. Heat Mass Transfer, **55**(17–18), pp. 4744–4753.
[22] Bejan, A., and Errera, M. R., 2000, "Convective Trees of Fluid Channels for Volumetric Cooling," Int. J. Heat Mass Transfer, **43**(17), pp. 3105–3118.
[23] Bejan, A., 2005, "The Constructal Law of Organization in Nature: Tree-Shaped Flows and Body Size," J. Exp. Biol., **208**(9), pp. 1677–1686.
[24] Reis, H., 2006, "Constructal View of Scaling Laws of River Basins," Geomorphology, **78**, pp. 201–206.
[25] Miguel, A. F., and Bejan, A., 2009, "The Principle That Generates Dissimilar Patterns Inside Aggregates of Organisms," J. Phys. A, **388**, pp. 727–731.
[26] Herrera, M. R., and Marin, C. A., 2009, "A Comparison Between Random and Deterministic Dynamics of River Drainage Basins Formation," Therm. Eng., **8**(1), pp. 65–71.
[27] Miguel, A., 2010, "Natural Flow Systems: Acquiring Their Constructal Morphology," Int. J. Des. Nat. Ecodyn., **5**(3), pp. 230–241.
[28] Lorente, S., and Bejan, A., 2010, "Few Large and Many Small: Hierarchy in Movement on Earth," Int. J. Des. Nat. Ecodyn., **5**(3), pp. 1–14.
[29] Bejan, A., 2010, "The Constructal Law Origin of the Wheel, Size, and Skeleton in Animal Design," Am. J. Phys., **78**(7), pp. 692–699.
[30] Reis, H., 2011, "Design in Nature, and the Laws of Physics," Phys. Life Rev., **8**(3), pp. 255–256.
[31] Bejan, A., and Almogbel, M., 2000, "T-Shaped Fins," Int. J. Heat Mass Transfer, **43**(12), pp. 2101–2115.
[32] Zamfirescu, C., and Bejan, A., 2003, "Constructal Tree-Shaped Two-Phase Flow for Cooling a Surface," Int. J. Heat Mass Transfer, **46**(15), pp. 2785–2797.
[33] Ding, X., and Yamazaki, K., 2005, "Constructal Design of Cooling Channel in Heat Transfer System by Utilizing Optimality of Branch Systems in Nature," ASME J. Heat Transfer, **129**(3), pp. 245–255.
[34] Zimparov, V. D., da Silva, A. K., and Bejan, A., 2006, "Thermodynamic Optimization of Tree-Shaped Flow Geometries With Constant Channel Wall Temperature," Int. J. Heat Mass Transfer, **49**(25–26), pp. 4839–4849.
[35] Rocha, L., Lorenzini, E., and Biserni, C., 2005, "Geometric Optimization of Shapes on the Basis of Bejan's Constructal Theory," Int. Commun. Heat Mass Transfer, **32**(10), pp. 1281–1288.
[36] Moreno, R. M., and Tao, Y. X., 2006, "Thermal and Flow Performance of a Microconvective Heat Sink With Three-Dimensional Constructal Channel Configuration," ASME J. Heat Transfer, **128**(8), pp. 740–751.
[37] Zhang, X., and Liu, D., 2010, "Optimum Geometric Arrangement of Vertical Rectangular Fin Arrays in Natural Convection," Energy Conv. Manage., **51**(12), pp. 2449–2456.
[38] Lorenzini, G., and Moretti, S., 2009, "A Bejan's Constructal Theory Approach to the Overall Optimization of Heat Exchanging Finned Modules With Air in Forced Convection and Laminar Flow Condition," ASME J. Heat Transfer, **131**(8), p. 081801.
[39] Lorenzini, G., and Moretti, S., 2011, "Bejan's Constructal Theory Analysis of Gas–Liquid Cooled Finned Modules," ASME J. Heat Transfer, **133**(7), p. 071801.
[40] Hajmohammadi, M. R., Campo, A., Nourazar, S. S., and Ostad, A. M., 2013, "Improvement of Forced Convection Cooling Due to the Attachment of Heat Sources to a Conducting Thick Plate," ASME J. Heat Transfer, **135**(12), p. 124504.
[41] Hajmohammadi, M. R., Moulod, M., Joneydi Shariatzadeh, O., and Campo, A., 2014, "Effects of a Thick Plate on the Excess Temperature of Iso-Heat Flux Heat Sources Cooled by Laminar Forced Convection Flow: Conjugate Analysis," Numer. Heat Transfer, Part A, **66**(2), pp. 205–216.
[42] Rocha, L., Montanari, G. C., Dos Santos, E. D., and Rocha, A. D., 2007, "Constructal Design Applied to the Study of Cavities," Therm. Eng., **6**, pp. 41–47.
[43] Hajmohammadi, M. R., Poozesha, S., Campo, A., and Nourazar, S. S., 2013, "Valuable Reconsideration in the Constructal Design of Cavities," Energy Conv. Manage., **66**, pp. 33–40.
[44] Lorenzini, G., Biserni, E., Estrada, E. D., Isoldi, L. A., dos Santos, E. D., and Rocha, L. A. O., 2014, "Constructal Design of Convective Y-Shaped Cavities by Means of Genetic Algorithm," ASME J. Heat Transfer, **136**(7), p. 071702.
[45] Lorenzini, G., da Silva Diaz Estrada, E., dos Santos, E. D., Isoldi, L. A., and Rocha, L. A. O., 2015, "Constructal Design of Convective Cavities Inserted Into a Cylindrical Solid Body for Cooling," Int. J. Heat Mass Transfer, **83**, pp. 75–83.
[46] UNI, 2008, "Materiali e Prodotti per Edilizia – Procedimenti per la Determinazione dei Valori Termici Dichiarati e di Progetto," Italian Organization for Standardization, Rome, Italy, Standard No. UNI EN ISO 10456.
[47] Norton, P., and Christensen, C., 2006, "A Cold-Climate Case Study for Affordable Zero Energy Homes," Solar 2006 Conference, Denver, CO, July 9–13, pp. 591–595.
[48] Feist, W., 2011, "Certified Passive House—Certification Criteria for Residential Passive House Buildings," Passive House Institute, Darmstadt, Germany.
[49] VVAA, 2008, "Engineering and Operating Guide for DOWTHERM SR-1 and DOWTHERM 4000 Inhibited Ethylene Glycol-Based Heat Transfer Fluids," The Dow Chemical Company, Midland, MI.
[50] Fanger, P. O., 1970, *Thermal Comfort*, Danish Technical Press, Copenhagen, Denmark.
[51] VVAA, 1999, *ASHRAE Handbook CD 1999–2002*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
[52] VVAA, 1994, "Moderate Thermal Environment: Determination of PMV and PPD Indies and Specification of the Conditions for Thermal Environment," International Organization for Standardization, Geneva, Switzerland, Standard No. 7730.
[53] Indraganti, M., and Daryani Rao, K., 2010, "Effect of Age, Gender, Economic Group and Tenure on Thermal Comfort: A Field Study in Residential Buildings in Hot and Dry Climate With Seasonal Variations," Energy Build., **42**(3), pp. 273–281.
[54] UNI, 2008, "Prestazioni Energetiche Degli Edifici—Parte 1: Determinazione del Fabbisogno di Energia Termica Dell'edificio per la Climatizzazione Estiva ed Invernale," Italian Organization for Standardization, Rome, Italy, Standard No. UNI/TS11300-1.
[55] Baltay, P., and Gjelsvik, A., 1990, "Coefficient of Friction for Steel on Concrete at High Normal Stress," J. Mater. Civil Eng., **2**(1), pp. 46–49.
[56] Churchill, S. W., 1977, "Friction Factor Equation Spans All Fluid-Flow Regimes," Chem. Eng., **91**.
[57] Lloyd, J. R., and Moran, W. R., 1974, "Natural Convection Adjacent to Horizontal Surfaces of Various Platforms," ASME J. Heat Transfer, **96**(4), pp. 443–447.
[58] Churchill, S. W., and Chu, H. H., 1975, "Correlating Equations for Laminar and Turbulent Free Convection From a Vertical Plate," Int. J. Heat Mass Transfer, **18**(11), pp. 1323–1329.