Thermal Mass: The Traditional Environmental Building Block

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KEYWORDS

Thermal Mass, Storage Gain, Building Blocks, Modelling, Dimensional Grouping, Dynamic Programming, Taming Synthesis.

ABSTRACT

Although thermal mass manifested itself as the traditional (environmental) building block through ancient history to modern society, computational modelling and innovative state of art implementation schemes lend a new dimension to this fundamental envelope substance. This paper hence relates to a computational model and implementation scheme in support of the concept of Free-Cool HVAC. As a sequel, a dimensionless response corollary, the universal storage corollary, has been developed via dimensional structuring of the basic model equations and performance synthesis via Dynamic Programming. This scheme appropriately named as the USC (viz Universal Storage Corollary) and which is formally being introduced via this presentation, should prove a powerful design tool for Engineers and Architects in equating the cyclic response gain of a thermal mass system.

Masse Thermale: L’environnement traditionnel Cubes de Construction

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NOTES CLÉS

Masse thermale, réservoir acquis, cubes de construction, création, groupement de Dimension, programmation dynamique, synthèse d’équipe.

RÉSUMÉ

Bien que la masse thermale se soit montrée comme le matériel de construction traditionnel (pour l’environnement) depuis l’histoire ancienne jusqu’aux temps modernes, les modèles calculables et la réalisation des projets de l’art innovateur prête une nouvelle dimension à cette substance d’enveloppement fondamentale. C’est pour cette raison que ce document fait des relations à un modèle calculable et à la mise en œuvre du projet en support du concept de Refroidissement. Libre HVAC Par suite, une réponse corollaire sans limite, a été développée par des structures à plusieurs dimensions du modèle de base d’équation et la synthèse de performance par la Programmation Dynamique. Ce projet qui porte le nom approprié de USC et qui est formellement introduit par cette présentation devrait, se montrer un outil de création puissant pour les ingénieurs et architectes en égalisant l’avantage de la réponse cyclique d’un système de masse thermale.
INTRODUCTION

Thermal mass has been the cornerstone of environmental comfort throughout ancient history via cave shelters, Egyptian pyramids, Inca abodes, colonial mansions, escorial igloos, etc. etc. Unfortunately the art of the (incipient) passive cooling/heating schemes as improvised by our predecessors over numerous centuries has been lost in the post WW II era. Floor-to-floor carpeting, dry-wall partitioning, steel and timber framed structures and false ceilings corrupted the previously passive environmental harmony. In addition, high illumination heat dissipation, poor building orientation and curtain wall perimeter glazing impaired the effectiveness ventilative aspiration and in fact necessitated the implementation of powerful HVAC in otherwise mild climatic areas. Fortunately the energy crisis of the early seventies rationalized the diverging trends and manifested new wisdom in the building profession.

FREE-COOL HVAC

Free-Cool HVAC is the HVAC process whereby refrigerated cooling may be obviated in lieu of passive and evaporative cooling forces. Free-cooling requires efficient shading, illumination and passive cooling schemes in manifesting the ultimate objective of obviating refrigerated cooling. In this context the concepts of smart glass, semi-task low-brightness luminaires, luminaire aspiration, day-lighting, two phase and cascaded evaporative cooling, reverse diffuser etc, may be recorded. Typically a working Free-Cool environment requires illumination dissipation < 12 Watts/m², no direct sunlight, free-glazing < 30% floor slabs > 150 mm and summer wet bulbs < 20°C. However various climatic and building parameter ranges may be structured via the DP (Dynamic Programming) synthesis. A shorthand design procedure, via the USC (2,3) has been developed comprising response charts with dimensionless parameters as per Fig. 1. Given hence the dimensionless group II₃ (the dimensionless primary heat flux) as fixed, the dimensionless groups II₄ and II₅ render the correlations otherwise completely universal in terms of structural mass, heat capacity, response period etc. etc. The singular parameter q₄, represents the heat load per unit area in consideration.

SIMULATION MODEL

The simulation model, which was developed at UCLA in 1972, comprises an elementary room system with a passive wall and a residue term representing the hourly heat load incidence. The hourly heat loads are evaluated in the model system via superpositioning and may be solved for separately with custom commercial computer programs sourced later alta via APEC, DOE, etc. etc. In accordance with Fig. 2.a and references 1 - 4 the model equations may hence be denoted as follows:

1. Fourier transient heat conduction equation in one dimension:

\[ \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2} \]

where \( T \) = temperature
\( t \) = time
\( \alpha \) = wall depth
\( \alpha_w \) = wall diffusivity

2. The room equilibrium differential equation:

\[ \frac{dT_r}{dt} = \frac{m(T_s - T_r) + h_A(T_r - T_b) + q_t/mc_{pa}}{mc_{pa}A_f} \]

where \( T_r \) = wall temperature
\( T_s \) = supply air temperature
\( T_b \) = room (bulk) air temperature
\( \alpha \) = wall depth
\( q_t \) = residue term
\( h_A \) = wall convection coefficient
\( A_f \) = area wall
\( c_{pa} \) = specific heat of air

The term \( q_t \) denotes the time discrete room heat loads which may be evaluated for off-line and simply equated by superpositioning.
In accordance with the Central Differencing theorem and nodal system per Fig. 2.b, eqns (1) and (2) may hence be differenced in terms of time and space parameters via the m and j nodes respectively as follows:

**Equation (1):**

\[ T_{wij}^{n+1} = \alpha \frac{C_w}{\Delta x^2} (T_{wij}^{n+1} - T_{wij}^{n+1}) + T_{wij}^{n} \]  

(3)

**Equation (2):**

\[ T_{b}^{n+1} = \Delta \frac{m}{\Delta t} \left( T_{n+1}^{n+1} + \frac{A C_w}{m C_p A_t} T_{n+1}^{n+1} + \frac{\Delta t}{m C_p A_t} q^{n+1} + T_{b}^{n+1} \right) \]  

(4)

where \( \delta = (1 - \delta) \)

\[ \delta = -\left( \frac{h_w A_t}{m C_p A_t} + \frac{w}{m} \right) \Delta t \]

Equating hence the node j as j-1, eqn. (3) may be restructured as:

\[ T_{wij}^{n+1} = \alpha \frac{C_w}{\Delta x^2} (T_{wij}^{n+1} - T_{wij}^{n+1}) + T_{wij}^{n+1} \]

(3a)

and (cross) substituting eqn. (3a) now into eqn (3) in accordance with the Patankar-Eppling synthesis (4), the recursive difference-equation system eqns. (5) and (6) is rendered as:

\[ T_{wij}^{n+1} = A_j^{\ast \ast} \cdot T_{wij}^{n+1} + B_j^{\ast \ast} \]  

(5)

with \( A_j^{\ast \ast} = \frac{A_j^{\ast}}{1-B_j^{\ast \ast}} \)

\[ B_j^{\ast \ast} = \frac{B_j^{\ast \ast} + C_j^{\ast}}{1-B_j^{\ast \ast}} \]

(5a)

**Equations (5) and (6) represent a unique and powerful HVAC model system wherein that the variables are i) completely recursive in TIME and SPACE hence i) obviating the need for compromising numerical computational procedures (viz. iterations) and ii) solving the standard heat load profiles off-line with commercially available (trial-and-tested) automated packages.**

The inside and outside boundary conditions may consequently be equated as:

\[ T_{2}^{n+1} = A_2^{\ast \ast} \cdot T_{3}^{n+1} + 0 \cdot T_{4}^{n+1} + C_2^{\ast} \]  

(5a)

with \( A_2^{\ast \ast} \) and \( C_2^{\ast} \) the equated inside boundary factorials

with \( B_2^{\ast \ast} = 0 \), and

\[ T_{j}^{n+1} = 0 \cdot T_{j+1}^{n+1} + B_j^{\ast \ast} \cdot T_{j-1}^{n+1} + C_j^{\ast} \]  

(5b)

where \( B_j^{\ast \ast} \) and \( C_j^{\ast} \) the equated (outside) boundary factorials with \( A_j^{\ast} = 0 \).

The differenced equilibrium equation system eqn. (4) may accordingly be rewritten into the following recursive structure viz.
\[ T_{n+1}^b = T_n^b + D^* T_n^b + F^* T_n^b + G^* T_n^b \] (6)

with \( D^* \), \( E^* \), \( F^* \) and \( G^* \) the system functional factorials.

**DIMENSIONAL GROUPING AND OPTIMALITY SYNTHESIS**

Defining now \( x = T_{s} / T_{s0} \) with \( T_{s0} = T_{s0} - T_{s} \) and \( T_{s0} = T_{s0} / T_{s} \) with \( T_{s0} \) the system time constant and \( y = y / d \) with \( d \) the wall thickness, eqns. (1) and (2) may hence be multiplied of the operators \( (T_{s0} / T_{s0}) \); \((d / d)^2\) and \((T_{s0} / T_{s0})\) be dimensionally restructured as:

\[ \frac{\partial x}{\partial t} = II_1 \frac{\partial^2 x}{\partial y^2} \] (7)

\[ \frac{dx}{dt} = II_2 (x - x_b) + II_3 (x - x_b) \cdot A_2 + II_4 \] (8)

viz. the dimensionless Fourier and equilibrium equations respectively with \( II_1 = \frac{A_2}{m T_{s0}} \), \( II_2 = \frac{m T_{s0} / m}{m T_{s0}} \), \( II_3 = \frac{A_2}{m T_{s0}} \) and \( II_4 = \frac{m T_{s0} / m}{m T_{s0}} \) with \( A_2 = A_2 / A_2 \), \( m = m / \).

Given now the optimality principle of Bellman 5, viz. for a given decision to be optimal all subsequent decisions have to be (equally) optimal, the dimensionless model equations, eqns. (7) and (8) may be solved and structured into the desired corollary Fig. 1. via the DP recursion:

\[ \min_{D_{n+1}} f_{n}(x_n) = \text{feas} \left[ g_{n}(x_{n} D_{n+1} + f_{n}(x_{n} + 1) \right] \] (9)

with \( f_{n}(x_n) \) the dynamic return (viz. total resource requirement), \( g_{n}(x_{n} D_{n+1}) \) the stage resource and \( \{D_{n+1}\} \) the (feasible) stage decision options. In the HVAC scenario the resource denotes the energy requirement and the feasible decisions simply the machinery functional capacity range (viz. cooling capacity) in terms of primary supply air temperature.

**CASE STUDY**

As illustration of the USC charts the following elementary case study has been structured:

1. **Nominal example:**

   - (1) Luminair dissipation: 20 Watts/m²
   - (2) People heat (sensible): 7.5 Watts/m²
   - (3) Diffuse radiation: 20 Watts/m²
   - (4) Equipment load: 7.5 Watts/m²
   - **Total**: 55 Watts/m²
   - **Eqv. Btu/ft² Total**: 18 Btu/ft²h

2. **F-C example:**

   - (1) Luminair dissipation: 12 Watts/m²
   - (2) People heat (sensible): 7.5 Watts/m²
   - (3) Diffuse radiation: 10 Watts/m²
   - (4) Equipment load: 2.5 Watts/m²
   - **Sub total**: 26 Watts/m²
   - **Eqv. Btu/ft² Total**: 9.2 Btu/ft²h

**Case Study**

Given the passive gain per the USC Fig. 1, the storage gain factor \( I_{l1} = 2.25 \) for \( \eta = 0.25 \) and \( I_{l1} = 0.31 \) (viz. a 6 inch concrete slab). The adjusted heat load hence is \( 6.2 / 2.25 = 3.6 \text{ Btu/ft²h} \) and the associated supply air temperature differential is \( 3.6^\circ F = 2^\circ C \).

The HVAC performance gain with a supply air \( \Delta t = 2^\circ C \) only vs. the nominal \( 10^\circ C \) is quite profound and manifests the Free-Cool objective. Clearly the supply air differential of \( 2^\circ C \) will not present an evaporative problem in most climatic areas!
REFERENCES


(b) GRAPHICAL REPRESENTATION

<table>
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<tr>
<th>d (in)</th>
<th>q (Btu/hr ft²)</th>
<th>T₅ (°F)</th>
<th>T₆ (°F)</th>
<th>ΔT₅ (°F)</th>
<th>II₄</th>
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<td>5.5</td>
<td>1.5</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>8 inch (200mm)</td>
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<td>68.2</td>
<td>70.0</td>
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<td>2.7</td>
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a = 5 lb/ft² hydraulic capacity 0.25 (Btu/ft²°F)

s = 0.6 lb/ft² h₃ = 1.0Btu/ft² h°F d = 0.02 ft²/h

(a) INPUT DATA

FIG 1. UNIVERSAL STORAGE COROLLARY
TRANSFER OF INFORMATION VIA DRAWINGS

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ABSTRACT

The increasing complexity of construction works and the developments taking place in the area of computer-aided design and construction make a uniform method for the compilation and transfer of graphical information absolutely essential. The whole process of construction preparation can be seen as an information-processor operation. In this operation drawings only form a part of the communication between the various partners involved in the building-process.

Drawings in general, contain information which cannot be transferred in any other form. Effective communication can only be achieved when the information contained correspond to the information required.

Investigations are in progress at SRH directed towards the development of a system for information-processing on drawings which will offer a uniform basis for the introduction and use of computerized information systems.

Computerized data-processing requires information which is in such a form that it can be readily processed by the computer. Characteristic of modern CAD/CAM systems is the processing of information in layers of levels and its compilation into elements and element-groups. In these systems elements are introduced or 'drawn' by forms (line, circle, triangle, right angle, etc). Compilation into elements takes place at each level of the building components. A level-distinction function makes it possible to link together information and also for partners in the building process to exchange information at any particular level.

The objective and content of the information can be determined from the construction preparation process. Information required can be established from the project objectives deduced per phase.

FIG 2. HVAC MODEL SYSTEM