Thermal Mass: The Traditional Environmental Building Block

Charl E. Janeke

University of the Witwatersrand Technological Centre (UwTEC)
1 Jan Smuts Avenue, Johannesburg 2000, South Africa

KEYWORDS

Thermal Mass, Storage Gain, Building Blocks, Modelling, Dimensional Grouping, Dynamic Programming, Teaming 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

Charl E. Janeke

University of the Witwatersrand Technological Centre (UwTEC)
1 Jan Smuts Avenue, Johannesburg 2000, South Africa

MOTS 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 modéles calculables et la réalisation des projets de l'art innovateur prête une nouvelle dimension á cette substance d'enveloppement fondamentale. C'est pour cette raison que ce document fait des relations á un modéle calculable et á la mise en ceuvre du projet en support du concept de Refroidissement. Libre HVAC Par suite, une réponse corollaire sans limite, a été développée par des structures á plusieurs dimensions du modéle de base d'équation et la synthése 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 systéme 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, escimo 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 1) 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** glas, semi-task low-brightness lumenaires, lumenaire aspiration, day-lighting, two phase and cascaded evaporative cooling, reverse diffuser etc, may be recorded. Typically a working Free-Cool environment requires illumination dissipation $\leq$ 12 Watts/m^2, no direct sunlight, free-glazing $\leq$ 30% floor slabs $\geq$ 150 mm and summer wet bulbs $\leq$ 20^{o}C. However various climatic and building parameter ranges may be structured via the DP (Dynamic Programming) synthesis. A shorthand design procedure, viz the **USC** (2,3) has been developed comprising response charts with dimensionless parameters as per Fig. 1. Given hence the dimensionless group II_1 (the dimensionless primary heat flux) as fixed, the dimensionless groups II_3 and II_4 render the correlations otherwise completely **universal** in terms of structural mass, heat capacity, response period etc. etc. The singular parameter q_I, represents the heat load per unit area in consideration.

SIMULATION MODEL

The simulation model, which was developed at UCLA in 1972 4), comprises an elementary **room** system with a **passive** wall and a **residue** term representing the hourly heat load incidence. The hourly heat loads are equated in the model system via superpositioning and may be solved for separately with custom commercial computer programs sourced inter alia 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:

$$\frac{\partial Tw}{\partial t} = \alpha w \frac{\partial^2 Tw}{\partial y^2} \qquad (1)$$

where T = temperature
t = time
y = wall depth
α_w = wall diffusity

2. The room equilibrium differential equation:

$$\frac{dT_w}{dt} = \frac{\mathbf{m}}{m}(T_s - T_b) + \frac{h_w A_w}{mC_{pa}A_f}(T_w - T_b) + q_I/mC_{pa} \qquad (2)$$

where T_w = **wall** temperature
T_s = supply air temperature
T_b = room (bulk) air temperature
t = time
y = wall depth
q_I = **residue** term
h_w = **wall** convection coefficient
A_w = area **wall**
A_f = area **floor**
C_{pa} = specific heat of air

The term q_I denotes the time discrete room heat loads which may be solved 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 n and j nodes respectively as follows;

Equation (1) :

$$T_{wj}^{n+1} = \frac{\Delta t \alpha_w}{x^2} [T_{wj+1}^{n+1} - T_{wj-1}^{n+1}] + T_{wj}^{n} \tag{3}$$

Equation (2) :

$$T_b^{n+1} = \frac{\Delta t m}{m} T_s^{n+1} + \frac{\Delta t h_w A_w}{m C_{pa} A_t \$} T_s^{n+1} + \frac{\Delta t}{m C_{pa}} q_I^{n+1} + T_b^n / \$ \tag{4}$$

where $\$_{,} = (1 - \$^{'})$
$\$^{'} = -(h_w A_w / m C_{pa} A_f + w/m)\ \Delta t$

Equating hence the node j as j=j+1, eqn. (3) may be restructured as;

$$T_{wj+1}^{n+1} = \frac{\Delta t \alpha_w}{\Delta x^2} [T_{wj+2}^{n+1} - T_{wj}^{n+1}] + T_{wj+1}^{n} \tag{3a}$$

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

$$T_{wj}^{n+1} = A_j^{**} \cdot T_{wj+1}^{n+1} + B_j^{**} \tag{5}$$

$$\text{with } A_j^{**} = \frac{A_j^*}{1 - B_j^* A_{j-1}^{**}}$$

$$B_j^{**} = \frac{B_j^* B_{j-1}^{**} + C_j^*}{1 - B_j^* A_{j-1}^{**}}$$

with A_j^*, B_j^* and C_j^* being the sytem functional factorials.

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

The inside and outside boundary conditions may conversely be equated as;

$$T_2^{n+1} = A_2^{*'} . T_3^{n+1} + 0 \ . \ T_1^{n+1} + C_2^{*'} \tag{5a}$$

with $A_2^{*'}$ and $C_2^{*'}$ the **equated** inside boundary factorials

with $B_2^{*'}$ =0, and

$$T_J^{n+1} = 0 . \ T_{J+1}^{n+1} + B_J^{*'} \ . \ T_{J-1}^{n+1} + C_J^{*'} \tag{5b}$$

where $B_J^{*'}$ and $C_J^{*'}$ the **equated** (outside) boundary

factorials with $A_J^{*'}$=0.

The differenced equilibrium equation system eqn. (4) may accordingly be rewritten into the following recursive structure viz;

$$T_b^{n+1} = E^*.T_s^{n+1} + D^*.T_2^{n+1} + F^*.q_I^{n+1} + G^*T_b^n \qquad (6)$$

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

DIMENSIONAL GROUPING AND OPTIMALITY SYNTHESIS

Defining now $x=T/\Delta T_s$ with $\Delta T_s=T_b-T_s$, $\Delta t=t/\tau$ with τ the system time constant and $y=y/d$ with d the wall thickness, eqns. (1) and (2) may hence by multiplication of the operators $(\tau/\Delta T_s)$;$(d/d)^2$ and $(\tau/\Delta T_s)$ be dimensionally restructured as;

$$\frac{\partial x_w}{\partial t} = II_1 \frac{\partial^2 x}{\partial y^2} \qquad (7)$$

$$\frac{dx_b}{dt} = II_2(x_s-x_b)+II_3(x_s-x_b).A_R+II_4 \qquad (8)$$

viz. the dimensionless Fourier and equilibrium equations respectively with $II_1=N_F=[\alpha w\tau/d^2]$, $II_2=[m\tau/m]=1$, $II_3=[\alpha_2/mC_{pa}]$ and $II_4=[q_I/mC_{pa}\Delta T_s]$ with $A_R=A_w/A_f$, $m=m/\tau$.

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) maybe solved and structured into the desired corollary Fig. 1. via the DP recursion;

$$f_n(x_n) = \min_{\substack{\text{feas} \\ \langle D_{n+1}'s\rangle}} [g_n(x_n D_{n+1})+f_n(x_{n+1})] \qquad (9)$$

with $f_n(x_n/x_{n+1})$ the **dynamic** return (viz. total resource requirement), $g_n(x_n D_{n+1})$ the stage resource and $\langle D_{n+1}\rangle$ the (feasible) stage decision options. In the HVAC scenario the **resource** denotes the energy requirement and the **feasible decisions** simply the machinery functional capability 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)	Lumenair dissipation	20 Watts/m^2
(2)	People heat (sensible)	7,5 Watts/m^2
(3)	Diffuse radiation	20 Watts/m^2
(4)	Equipment load	7,5 Watts/m^2
	Total	55 Watts/m^2
	Eqv. Btu/ft^2 Total	18 Btu/ft^{2}h

2. F-C example:

(1)	Lumenair dissipation	12 Watts/m2
	less (50%) "aspiration" gain	- 6 Watts/m^2
(2)	People heat (sensible)	7,5 Watts/m^2
(3)	Diffuse radiation	10 Watts/m^2
(4)	Equipment load	2,5 Watts/m^2
	Sub total	26 Watts/m^2
	Eqv. Btu/ft^2 Total	8,2 Btu/ft^{2}h

Given the **passive** gain per the **USC** Fig. 1, the storage gain factor II_4 = 2,25 for q_I = 8,2 and II_1 = 0,31 (viz. a 6 inch concrete slab). The adjusted heat load hence = 8,2/2,25 = 3,6 Btu/ft^{2}h and the associated supply air temperature differential = 3,6°F = 2°C.

The HVAC performance gain with a supply air Δt = 2°C only vs. the nominal 10°C is quite profound and manivests the Free-Cool objective. Clearly the supply air differential of 2°C will not present an **evaporative** problem in most climatic areas!

= oOo =

REFERENCES

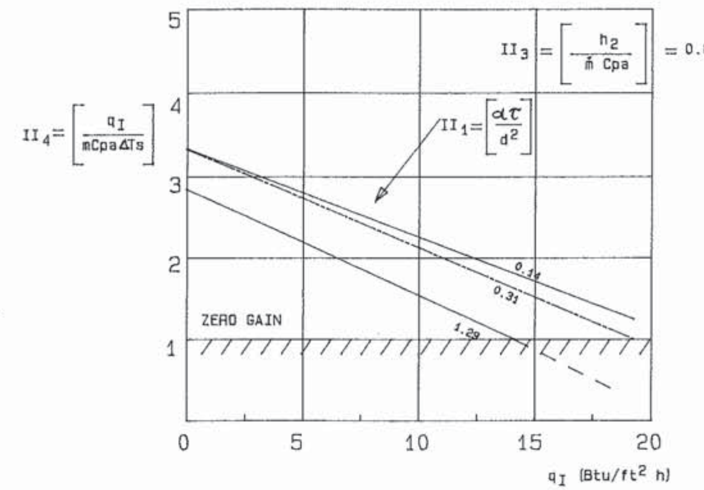
1. JANEKE, C.E. Free-Cool: A Total HVAC Design Concept. ASHRAE Technical Seminar, Houston, January 1982.

2. JANEKE, C.E. Fenestration and Thermal Rotation - The ABC of Free-Cool HVAC. Thermal Performance of the Exterior Envelopes of Buildings 111. ASHRAE DOE-BTECC Conference, Clearwater, Florida, December 1985.

3. JANEKE, C.E. Modelling Techniques, Parameter Determination and Optimal Control of Energy Distribution in Large Building Structures, Rand, October 1985.

4. JANEKE & DENNY. Thermal Response of Ventilated Structures. Project report 231D, UCLA, 1972.

5. BELLMAN & DREYFUSS. Applied Dynamic Programming. Princeton University Press, 1962.



(b) GRAPHICAL REPRESENTATION

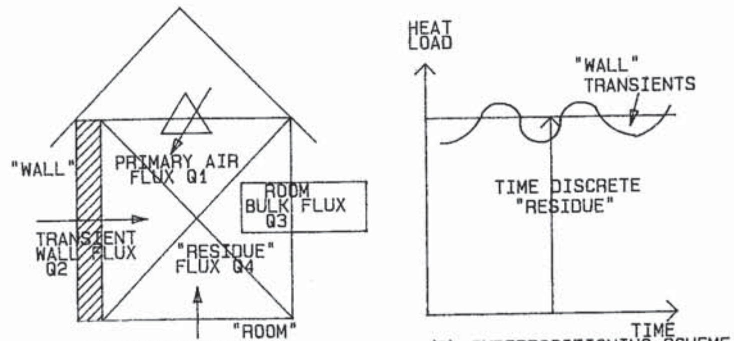
d	q_I (Btu/hft^2)	T_S (°F)	T_b (°F)	ΔT_S (°F)	II_4
4inch (100mm)	5	69.7	71.5	1.8	2.2
4inch (100mm)	10	67.0	72.5	5.5	1.5
4inch (100mm)	15	-	-	-	-
8inch (200mm)	5	69.2	70.0	1.5	2.7
8inch (200mm)	10	70.6	74.5	3.9	2.1
8inch (200mm)	15	66.1	74.0	7.9	1.5
12inch (300mm)	5	69.2	70.7	1.5	2.7
12inch (300mm)	10	70.5	74.3	3.8	2.1
12inch (300mm)	15	61.1	74.0	7.6	1.6

$\dot{m}$ = 5lb/hft^2 τ = 7h Cpa = 0.25 (Btu/lb°F)

m = 0.6lb/ft^2 h_2 = 1.0Btu/ft^{2}h°F α = 0.02ft^2/h

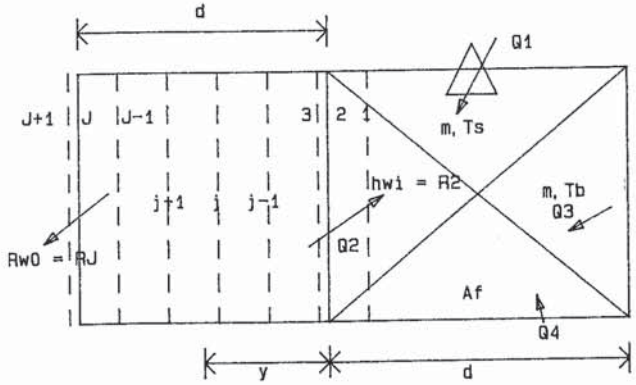
(a) INPUT DATA

FIG 1. UNIVERSAL STORAGE COROLLARY



(A) ROOM MODEL (B) SUPERPOSITIONING SCHEME

$$Q1 = mCpa\ Af\ (Tb-Ts)$$
$$Q2 = h2\ Aw\ (Tb-Ts)$$
$$Q3 = -(\Delta Tb/\Delta t)\ m\ Cpa\ Af$$
$$Q4 = Af\ qi$$
$$Q1 = Q2+Q3+Q4$$



(C) NODAL SYSTEM

FIG 2. HVAC MODEL SYSTEM

TRANSFER OF INFORMATION VIA DRAWINGS

J. A. Kooren

Stichting Bouwresearch
Weena 740
Postbus 20740
3001 JA Rotterdam
The Netherlands

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 SBR 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 dataprocessing 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 its 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.