ENERGY CONSERVATION IN AN ANCIENT PASSIVE BUILDING FOR A COMPOSITE CLIMATE

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Energy Conservation in an Ancient Passive Building for a Composite Climate

by

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Certificate

This is to certify that the thesis entitled "**Energy Conservation in an Ancient Passive Building for a Composite Climate"** being submitted by **Heena Fatima Ali** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of **'Doctor of Philosophy'** and is a record of the original bona fide research work carried out by her under our guidance and supervision at Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The results contained in the thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

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Abstract

The growing concerns about global warming and the depletion of fossil fuels have prompted architects to include energy-saving measures in their designs. Contemplating over the time-tested centuries old constructions and ancient buildings which aided in maintaining thermal comfort for occupants and providing daylight, without depending on the non-renewable energy sources, has inspired architects and builders to embrace the ancient design approaches. Solar energy, which is abundant in countries such as India, can be extremely resourceful in achieving this goal of alleviating energy consumption.

The thesis elucidates the developments made in the field of building energy conservation. It begins with a comprehensive review of the research endeavors towards incorporating passive design strategies within buildings, from where, it delves into the cardinal role of ancient architecture in energy conservation. New Delhi, the capital of India, has more than 170 ancient structures under Archeological survey of India which are yet to be explored for their energy performance aspect, though outside India only a few ancient structures are numerically investigated for their energy performance. Thus, a vernacular structure with ancient architecture, located in the composite climatic conditions of New Delhi has been selected for the case study. The findings of the study would help in the adoption of appropriate passive design technique in the modern-day constructions. It thus, becomes imperative to identify the passive solar design strategies of the vernacular building with ancient architecture that is drastically impacting the building's energy performance. This can lead to further understanding of the sustainable design principles and prioritize energy efficiency measures.

The study then investigates the energy saving potential of the passive solar design determinants identified in the case study building. Thermal modelling of the building has been performed to assess the annual total thermal energy savings. For this, hourly solar radiation,

illuminance level from daylighting, ambient temperature as well as temperature of the building have been measured, based on which, annual energy savings owing to the passive features have been assessed. This has been further used for the estimation of artificial lighting energy savings during the daytime and eventually the annual total energy savings. One of the salient elements of the case study building is the ‘Trombe’ wall, which has been studied in detail. Thickness of the wall has been varied to analyze its influence on the energy saving potential of the building. Further, the study attempts to analyse the energy performance of the vernacular architecture for its passive solar strategies employed and develop a code using MATLAB to assess the viability of the building present in the composite climate of New Delhi. The embodied energy, energy payback time (EPBT), energy production factor (EPF) and life-cycle conversion efficiencies (LCCE), forming the energy matrices, as well as CO_2 emissions, net CO_2 mitigation and carbon credits earned, forming the enviro-economics have also been evaluated. Further, the influence of parameters such as wall thickness, life of building and average daily solar intensity have been analyzed.

Finally, ‘Life-Cycle Cost Assessment’ has been performed on the case study building. A cash flow model is generated and analyzed, covering economic aspects from the time of the building’s construction to its expected life. It attempts to propose an ‘analysis-led-design’ strategy using MATLAB for builders and architects, providing a beforehand benefit-cost economic performance study for future ‘state-of-the-art’ building projects prior to their actual construction. A parametric study has been conducted for varying number of annual thermal energy saving days, interest rates, building timelines and wall thickness functioning as ‘Trombe’ wall.

This study would provide inputs to the architects to incorporate design features of ancient architecture into modern buildings from the first stage of building design itself – concept visualization, hence, encouraging architects to rely more on passive design strategies. It would also help in saving time and energy to be spent on building design encompassing appropriate passive techniques for energy saving by using building performance analysis tools.

सार

ग्लोबल वार्मिंग और जीवाश्म ईंधन (Fossil fuels) की कमी की वजह से बढ़ती चिंताओं ने वास्तकुार (architects) को अपने तरीकों में ऊर्जा-बचत उपायों को शामिल करने के लिए प्रेरित किया है। सदियों पुरानी बनी प्राचीन इमारतों पर विचार किया जा रहा है, जो बिना किसी नॉन रिन्यूएबल ऊर्जा स्रोत पर निर्भर हुए तापमान की राहत बनाए रखने और दिन के उजाले प्रदान करने में मदद करती हैं, और जो वास्तुकार और निर्माणकर्ता को प्राचीन बनावट के लिए प्रेरित करती हैं। सौर ऊर्जा, जो भारत जैसे देशों में पर्याप्त मात्रा में है, ऊर्जा खपत को कम करके इस लक्ष्य को प्राप्त करने में अत्यंत संसाधनपूर्ण (resourceful) हो सकती है।

यह शोध प्रबंध (thesis) ऊर्जा संरक्षण के क्षेत्र में किए गए विकास को स्पष्ट करता है। यह अनुसंधान प्रयास की व्यापक समीक्षा के साथ शुरू होता है, भवनों के भीतर निष्क्रिय डिजाइन रणनीतियों को शामिल करने की दिशा में, जहां से, यह ऊर्जा संरक्षण में प्राचीन वास्तुकला की मुख्य भूमिका में आता है। Archeological survey of India के अनुसार भारत की राजधानी, नई दिल्ली में 170 से अधिक प्राचीन संरचना है, जिसे अभी तक उनके ऊर्जा प्रदर्शन पहलू के लिए खोजा जाना बाकी है, भारत के बाहर कई प्राचीन संरचनाओं को उनके ऊर्जा प्रदर्शन के लिए संख्यात्मक रूप से जांचा जाता है। इसलिए, प्राचीन संरचना के साथ एक स्थानीय संरचना, नई दिल्ली की मिश्रित जलवायु परिस्थिति को केस स्टडी के लिए चुना गया है। इस अध्ययन का जो कुछ भी निष्कर्ष होगा, आधुनिक निर्माण में उपयुक्त डिजाइन तकनीक को अपनाने में मदद करेगा। इसलिए, यह अनिवार्य हो जाता है, प्राचीन वास्तुकला के साथ स्थानीय इमारत की निष्क्रिय सौर डिजाइन रणनीतियों की पहचान करें, जो इमारत के ऊर्जा प्रदर्शन को काफी प्रभावित कर रहा है। इससे लंबे समय तक टिकने वाले डिजाइन सिद्धांतों की और समझ पैदा हो सकती है और ऊर्जा दक्षता उपायों को प्राथमिकता दी जा सकती है।

इस अध्ययन की मदद से केस स्टडी बिल्डिंग में पहचाने गए निष्क्रिय सौर डिजाइन निर्धारकों की ऊर्जा बचत क्षमता की जांच होती है। वार्षिक कुल तापीय ऊर्जा बचत का आकलन करने के लिए भवन का थर्मल मॉडलिगं किया गया है। इसके लिए प्रति घंटा सौर विकिरण, दिन के उजाले से रोशनी का स्तर, परिवेश

का तापमान और साथ ही इमारत के तापमान को मापा गया है, जिसके आधार पर निष्क्रिय विशेषताओं के कारण वार्षिक ऊर्जा बचत का आकलन किया गया है। इसका उपयोग कृत्रिम प्रकाश ऊर्जा बचत के आकलन के लिए दिन के समय किया गया है, और सालाना कुल ऊर्जा बचत की बात की गई है। भवन केस स्टडी के मुख्य तत्वों में से एक 'ट्रॉम्बे' (Trombe) दीवार है जिसका विस्तार से अध्ययन किया गया है। भवन की ऊर्जा बचत क्षमता पर इसके प्रभाव का विश्लेषण करने के लिए दीवार की मोटाई में बदलाव किया गया है। इसके अलावा, अध्ययन अपनी निष्क्रिय सौर रणनीतियों के लिए स्थानीय वास्तुकला के ऊर्जा प्रदर्शन का विश्लेषण करने का प्रयास करता है और नई दिल्ली के समग्र वातावरण में मौजूद भवन की व्यवहार्यता का आकलन करने के लिए MATLAB का उपयोग करके एक कोड विकसित करता है। सन्निहित ऊर्जा, ऊर्जा लौटाने का समय (EPBT), ऊर्जा उत्पादन कारक (EPF) और जीवन-चक्र रूपांतरण दक्षता (LCCE), ऊर्जा मैट्रिक्स बनाने के साथ-साथ CO_2 उत्सर्जन, कुल CO_2 शमन और अर्जित कार्बन क्रेडिट, पर्यावरण-अर्थशास्त्र का गठन भी मूल्यांकन किया गया है। दीवार की मोटाई, भवन का जीवन और औसत दैनिक सौर तीव्रता जैसे मापदंडों का प्रभाव विश्लेषण किया गया है।

अंततः, मकानों के केस स्टडी पर 'जीवन-चक्र लागत मूल्यांकन' किया गया है। एक नकदी प्रवाह (cash flow) मॉडल तैयार किया जाता है और उसका विश्लेषण किया गया है, जिसमें भवन के निर्माण के समय उसके अपेक्षित जीवन तक से आर्थिक पहलुओं को शामिल किया गया है। यह बिल्डरों और आर्किटेक्ट्स के लिए MATLAB का उपयोग करके 'विश्लेषण-नेतृत्व-डिज़ाइन' (analysis-led-design) रणनीति का प्रस्ताव करने का प्रयास करता है, जो उनके वास्तविक निर्माण से पहले भविष्य की 'अत्याधुनिक' (state-of-the-art) निर्माण परियोजनाओं के लिए पहले से लाभ-लागत (benefit-cost) आर्थिक प्रदर्शन अध्ययन प्रदान करता है। वार्षिक थर्मल ऊर्जा बचत दिवसों, ब्याज दरों के निर्माण की समयसीमा और दीवार की मोटाई 'ट्रॉम्बे' दीवार के रूप में कार्य करने के लिए एक मापदंड अध्ययन किया गया है।

यह अध्ययन वास्तुकार को प्राचीन वास्तुकला की रूप-रेखा की खूबियों को आधुनिक वास्तुकला रूपरेखा में शामिल करने के लिए स्वयं-अवधारणा की कल्पना की क्षमता प्रदान करेगा, और, वास्तुकार को निष्क्रिय डिजाइन रणनीतियों में अधिक भरोसा करने के लिए प्रोत्साहित करेगा। यह समय और ऊर्जा को भी बचाने में मदद करेगा, जो भवन निर्माण में खर्च होती है, और बिल्डिंग परफॉर्मेंस एनालिसिस टूल का उपयोग करके ऊर्जा की बचत के लिए उपयुक्त निष्क्रिय तकनीक को शामिल करेगा।

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Nomenclature

A	Total area of the surface (m^2)
A_{floor}	Building floor area (m^2)
A_{01}	Prayer hall area (m^2)
A_{02}	Courtyard area (m^2)
A_{03}	Corridor area (m^2)
A_{wall}	Area of walls (m^2)
b_{wall}	Wall thickness (m)
B_{eff}	Total present value of total benefits throughout building's life (effective benefit) (Rs.)
B_{EoT}	Factor for equation of time
B_x	Total benefit at the end of x^{th} year (Rs.)
$B_{x,00}$	Present value of the total benefit at the end of x^{th} year (Rs.)
C_a	Specific heat of air (J/kg °C)
C_{bw}	Specific heat of clay brick wall (J/kg °C)
$C_{CO_2,N}$	Carbon credits earned (Rs.)
$CO_{2,emission,N}$	CO_2 emission over a lifetime of building (tonnes)
$CO_{2,Net\ mitigation,N}$	Net CO_2 mitigation over a lifetime of building (tonnes)
C_p	Specific heat (J/kg °C)
$\frac{dT}{dx}$	Temperature gradient (°C /m).
D	Disbenefits (Rs.)

E_{aout}	Total annual energy saved by building (MWh)
E_{aout1}	Annual total thermal energy saved by building (MWh)
E_{aout2}	Annual artificial lighting energy saved by building (MWh)
E_{in}	Embodied energy (MWh)
EoT	Equation of time (minutes)
h	Convective heat transfer coefficient (W/m^2°C)
ht_{01}	Prayer hall height (m)
ht_{02}	Courtyard height (m)
ht_{03}	Corridor height (m)
i	Rate of interest (%)
I_o	Extra-terrestrial irradiation on horizontal surface (W/m^2)
I_{SC}	Solar constant (W/m^2)
$I(t)$	Solar radiation intensity (W/m^2)
$\overline{I(t)}$	Average daily solar radiation intensity (W/m^2),
k	Thermal conductivity of the material (W/m K)
K_t	Sky clearness index
L_a	Electrical loss
L_{td}	Transmission and distribution loss
LST	Local solar time
$LSTM$	Local standard time meridian
LT	Local time
M	Mass (kg)

$M_{25\%\,wall}$	Mass of building walls with 25% wall thickness (kg)
$M_{50\%\,wall}$	Mass of building walls with 50% wall thickness (kg)
$M_{75\%\,wall}$	Mass of building walls with 75% wall thickness (kg)
n	Number of years
n_d	Number of clear sky days in a year
n_{day}	n^{th} day of the year
n_{dm}	Number of days in a month considered for indoor heating/cooling
n_{ds}	Number of days considered in summer months
n_{dw}	Number of days considered in winter months
n_h	Number of hours for indoor heating/cooling
n_{leh}	Number of hours of operation of lighting equipment during daytime
n_m	Quantity of building materials used
N	Building life (years)
N_{lei}	Number of artificial lighting equipment of i^{th} fixture type during daytime
P	Initial cost/expenditure (Rs.)
P_{30}	Initial cost/expenditure for '30-60' years' timeline (Rs.)
P_{eff}	Total present value of expenditure throughout building's life (effective expenditure) (Rs.)
P_{OMx}	Total operation-maintenance cost at the end of x^{th} year (Rs.)

$P_{OMx,00}$	Present value of the total operation-maintenance cost at the end of x^{th} year (Rs.)
P_{OMeff}	Total present value of the total operation-maintenance cost throughout building's life (effective operation-maintenance cost) (Rs.)
P_{OVx}	Overhauling cost at x^{th} year (Rs.)
$P_{OVx,00}$	Present value of overhauling cost at x^{th} year (Rs.)
P_{OVeff}	Total present value of total overhauling cost at each x^{th} year throughout building's life (effective overhauling cost) (Rs.)
$P_{\mathrm{We}i}$	Wattage per equipment of i^{th} fixture type (W)
$\Delta\mathrm{Q}$	Uncertainty in measurement of daily thermal energy saved in building (MWh)
$\frac{\partial \mathrm{Q}}{\partial \Delta \mathrm{T}}$	Partial derivative of measurement of daily thermal energy saved in building with respect to partial derivative of temperature difference
$\frac{\partial \mathrm{Q}}{\partial \mathrm{V}}$	Partial derivative of measurement of daily thermal energy saved in building with respect to partial derivative of volume of building
Q	Daily thermal energy saved in building (MWh)
Q_{a-sum}	Annual thermal energy saved in building in summers (MWh)
Q_{a-win}	Annual thermal energy saved in building in winters (MWh)
$\dot{Q}_c$	Rate of conduction heat transfer (W)
$\dot{Q}_{conv}$	Rate of convective heat transfer (W)

Q_i	Daily thermal energy saved in building for the ith day (MWh)
Q_{monthy}	Monthly thermal energy saved in building (MWh)
$\dot{Q}_r$	Rate of radiative heat transfer (W)
R_{OMx}	$Unacost$ of operation-maintenance (Rs.)
R_{Bx}	$Unacost$ of monetary benefits (Rs.)
R_c	Unit cost of thermal energy saved (Rs./kWh)
R_{et}	$Unacost$ of electrical tariff (Rs./kWh)
R_{Peff}	$Unacost$ of effective expenditure (Rs.)
S	Future cost (Rs.)
ΔΔT	Uncertainty in the measurement of temperature difference (°C)
ΔT	Temperature difference between indoor and ambient (°C)
ΔT_{GMT}	Time difference between meridian of a given place and the Greenwich time meridian
T_a	Ambient temperature (°C)
T_s	Temperature of surface (K)
TC	Time correction factor (minutes)
T_s	Temperature of the body (K)
U	Energy density of the material used in the building
ΔV	Uncertainty in the measurement of volume of building (m^3)
V	Volume of building (m^3)
V_{wall}	Volume of building walls (m^3)
$V_{25\%\,wall}$	Volume of building walls with 25% wall thickness (m^3)

$V_{50\%\,wall}$	Volume of building walls with 50% wall thickness (m^3)
$V_{75\%\,wall}$	Volume of building walls with 75% wall thickness (m^3)
w_m	Weight per unit of the building material (kg)

Greek letters

α_S	Solar altitude angle/ elevation angle (degree)
δ	Declination angle (degree)
ε	Emissivity of the body
ρ	Density of a material (kg/m^3)
ρ_a	Density of air (kg/m^3)
ρ_b	Density of clay brick (kg/m^3)
σ	Stefan-Boltzmann constant ($W/m^2.K^4$)
φ	Latitude of a place (degree)
ω	Hour angle (degree)

Abbreviations

BEE	Bureau of Energy Efficiency
BIM	Building Information Modelling
BIPVT	Building integrated photovoltaic thermal system
CO_2	Carbon dioxide
COVID	Corona virus disease
CPC	Compound parabolic concentrator

CRF	Capital recovery factor
EAHE	Earth – air heat exchanger
ECBC	Energy Conservation Building Code
EPBT	Energy payback time
EPF	Energy production factor
EUI	Energy usage intensity
GDP	Gross domestic product
GMT	Greenwich mean time
HVAC	Heating, ventilation and air-conditioning
LCC	Life cycle cost
LCCA	Life cycle cost assessment
LCCE	Life cycle conversion efficiency
nZEB	Net zero energy buildings
NBC	National building code
O&M	Operation-maintenance
OCED	Organization of Economic Cooperation and Development
PV	Photovoltaic
PVC	Polyvinyl chloride
PVT	Photovoltaic thermal
RCC	Reinforced cement concrete
Rs.	Indian rupees
sDA	Spatial daylight autonomy
UDI	Useful daylight illuminance

$Unacost$	Uniform annual cost
USA	United States of America
VGS	Vertical greenery system
WWR	Window to wall ratio

Subscripts

a	Annual
eff	Effective
x	Year at which calculations are being done
$x,00$	Amount calculated at year x with respect to value of money at the time of actual building construction (0^{th} year)
$x,30$	Amount calculated at year x with respect to value of money 30 years after building's original year of construction (30^{th} year)
	Amount calculated at year x with respect to value of money 60 years after building's original year of construction (30^{th} year)
OM	Operation-maintenance
OV	Overhauling