

# **CONTROL STRATEGIES FOR ENERGY-EFFICIENT OPERATION OF AIR- CONDITIONED BUILDINGS**

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OPERATION OF AIR- CONDITIONED BUILDINGS**

by

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**DEPARTMENT OF MECHANICAL ENGINEERING**

**Submitted**

**In fulfilment of the requirements of the degree of doctor of philosophy**

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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**Dedicated to**

My loving Parents ( **Dr Arumugam Sudalai and Smt. Parimala Sudalai** ) and  
my Sister ( **Ms. Ranjana Sudalai** ).

And

All my **inspiring faculty members**, who never lost faith in me and stood by me

# CERTIFICATE

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This is to certify that the thesis entitled “ Control Strategies for Energy-Efficient Operation of Air Conditioned Buildings ” being submitted by **Vinayak Sudalai ( Entry No. 2016MEZ8280 )** to the Indian Institute of Technology Delhi, New Delhi, India, for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him under our guidance and supervision at the Department of Mechanical Engineering, Indian Institute of Technology, Delhi, and the candidate has fulfilled the requirements for the submission of this thesis. This thesis, in our opinion, meets the requirements for granting a Ph.D. degree from this institution. As per our awareness, the results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the granting of any degree/diploma or certificate.

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Vinayak Sudalai

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# Abstract

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Higher global average temperatures, rising population and affordability of air conditioning is leading to a rapid increase in cooling demand. Based on this, the capacity of cooling equipment is expected to triple by 2050 and with current slow pace of energy efficiency improvements, this would result in more than doubling of electricity consumption. Emissions from cooling are predicted to increase to between 4.4 billion and 6.1 billion tons of carbon dioxide equivalent (CO<sub>2</sub>e) in 2050, accounting for more than 10 per cent of global projected emissions that year. To contribute to the actions needed to mitigate this risk, this research work presents impact analysis using a combination of passive and active intervention approaches using an EnergyPlus model for an air-conditioned office complex in New Delhi. Impact of passive cooling measures like external and internal shading can lower energy consumption by 16%-21% over a typical summer week. By moving to an active control strategy to regulate chilled water flow rate proportional to occupancy by replacing the CAV air handler with a VAV air distribution system, an additional seasonal energy savings potential of 12-13 % is identified. A study of this office complex and another air-conditioned lecture hall complex has been done to identify additional controls driven energy saving opportunities. Implementing measures to save energy are as critical or perhaps more critical in developing countries where the high initial cost of energy saving technology could be a deterrent. To address that, four, low cost, open source, IoT-enabled sensing devices have been developed indigenously together with the necessary data acquisition and storage solutions using Grafana and Google Compute Cloud. The entire solution has been tested and calibrated before installation at a small, air-conditioned office in New Delhi to collect data over a period of 5 months. The parameters measured were temperature, relative humidity, CO<sub>2</sub> and PM 2.5 concentrations, number of door openings, occupant count, occupancy and energy consumed by the air-conditioning unit. An

analysis of the data shifted the research focus from energy efficiency to addressing compromised IAQ during peak occupancy periods in an energy efficient manner. A CO<sub>2</sub> build up model was validated using site data. A ventilation term was introduced into the model and energy consumption compared between fixed and actively modulated ventilation rates. A low-cost occupancy-driven modulation of ventilation air was observed to lower the energy consumption by 32%. A prototype ventilation control system was developed and deployed at one of rooms adjacent to a laboratory. The benefit of introducing ventilation on occupant sense of acceptability of environment was validated through a feedback survey.

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## सार

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उच्च वैश्विक औसत तापमान, बढ़ती जनसंख्या और एयर कंडीशनिंग की सामर्थ्य के कारण शीतलन की मांग में तेजी से वृद्धि हो रही है। इसके आधार पर, शीतलन उपकरणों की क्षमता 2050 तक तीन गुना होने की उम्मीद है और ऊर्जा दक्षता में सुधार की वर्तमान धीमी गति के कारण, इसके परिणामस्वरूप बिजली की खपत दोगुनी से अधिक हो जाएगी। 2050 में शीतलन से उत्सर्जन 4.4 बिलियन से 6.1 बिलियन टन कार्बन डाइऑक्साइड समकक्ष (सीओ<sub>2</sub>ई) तक बढ़ने का अनुमान है, जो उस वर्ष वैश्विक अनुमानित उत्सर्जन का 10 प्रतिशत से अधिक है। इस जोखिम को कम करने के लिए आवश्यक कार्यों में योगदान देने के लिए, यह शोध कार्य नई दिल्ली में एक वातानुकूलित कार्यालय परिसर के लिए एनर्जीप्लस मॉडल का उपयोग करके निष्क्रिय और सक्रिय हस्तक्षेप दृष्टिकोण के संयोजन का उपयोग करके प्रभाव विश्लेषण प्रस्तुत करता है। बाहरी और आंतरिक छायांकन जैसे निष्क्रिय शीतलन उपायों के प्रभाव से सामान्य गर्मी के सप्ताह में ऊर्जा की खपत 16% -21% तक कम हो सकती है। सीएवी एयर हैंडलर को वीएवी वायु वितरण प्रणाली से प्रतिस्थापित करके अधिभोग के अनुपातिक रूप से ठंडे पानी के प्रवाह दर को विनियमित करने के लिए एक सक्रिय नियंत्रण रणनीति की ओर बढ़ने से, 11-16% की अतिरिक्त ऊर्जा बचत क्षमता की पहचान की जाती है। अतिरिक्त नियंत्रण संचालित ऊर्जा बचत के अवसरों की पहचान करने के लिए इस कार्यालय परिसर और एक अन्य वातानुकूलित व्याख्यान कक्ष परिसर का अध्ययन किया गया है। विकासशील देशों में ऊर्जा बचाने के उपायों को लागू करना उतना ही महत्वपूर्ण या शायद अधिक महत्वपूर्ण है जहां ऊर्जा बचत प्रौद्योगिकी की उच्च प्रारंभिक लागत एक बाधा हो सकती है। इसे संबोधित करने के लिए, चार, कम लागत, ओपन सोर्स, IoT-सक्षम सेंसिंग डिवाइस को ग्राफाना और Google कंप्यूट क्लाउड का उपयोग करके आवश्यक डेटा अधिग्रहण और भंडारण समाधान के साथ स्वदेशी रूप से विकसित किया गया है। 5 महीने की अवधि में डेटा एकत्र करने के लिए नई दिल्ली में एक छोटे, वातानुकूलित कार्यालय में स्थापना से पहले संपूर्ण समाधान का परीक्षण और

अंशांकन किया गया है। मापे गए पैरामीटर तापमान, सापेक्ष आर्द्रता, CO<sub>2</sub> और PM 2.5 सांद्रता, दरवाजे के खुलने की संख्या, रहने वालों की संख्या, अधिभोग और एयर कंडीशनिंग इकाई द्वारा खपत की गई ऊर्जा थे। डेटा के विश्लेषण ने अनुसंधान का ध्यान ऊर्जा दक्षता से हटाकर ऊर्जा कुशल तरीके से चरम अधिभोग अवधि के दौरान समझौता किए गए IAQ को संबोधित करने पर केंद्रित कर दिया। साइट डेटा का उपयोग करके CO<sub>2</sub> बिल्ड अप मॉडल को मान्य किया गया था। निश्चित और सक्रिय रूप से संशोधित वेंटिलेशन दरों के बीच तुलना में मॉडल और ऊर्जा खपत में एक वेंटिलेशन शब्द पेश किया गया था। ऊर्जा की खपत को 32% तक कम करने के लिए वेंटिलेशन वायु का कम लागत वाला अधिभोग-संचालित मॉड्यूलेशन देखा गया। एक प्रोटोटाइप वेंटिलेशन नियंत्रण प्रणाली विकसित की गई और प्रयोगशाला से सटे एक कमरे में तैनात की गई। वातावरण की स्वीकार्यता की भावना पर वेंटिलेशन शुरू करने के लाभ को एक फीडबैक सर्वेक्षण के माध्यम से मान्य किया गया था।

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## Nomenclature and abbreviations

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A	:	Area (m <sup>2</sup> )
V	:	Volume (m <sup>3</sup> )
HVAC	:	Heating, ventilation, and air conditioning
IEQ	:	Indoor environmental quality
IAQ	:	Indoor air quality
POTCE	:	Post-occupancy thermal comfort evaluation
FCU	:	Fan coil unit
AHU	:	Air handling unit
SPL	:	Sound pressure level
BAU	:	Business as usual
NV	:	Naturally ventilated
PMV	:	Predicted mean vote
IoT	:	Internet of things
ASHRAE	:	American society of heating refrigerating and a/c engineers
PCS	:	Personal comfort systems
ECBC	:	Energy conservation building code
ACDD	:	Adaptive comfort degree days
DCV	:	Demand-controlled ventilation
CAV	:	Constant air volume
VAV	:	Variable air volume
KPI	:	Key performance indicators
RBC	:	Rule-based control
KNN	:	k- nearest neighbour

EMCS	:	Energy management control system
BMS	:	Building management system
MPC	:	Model predictive control
LEED	:	Leadership in energy and environmental design
TR	:	Tonnes of refrigeration
SHR	:	Sensible heat ratio
CRS	:	Common reporting standard
AFDD	:	Automated fault detection and diagnostics
HDD	:	Heating degree days
MBE	:	Mean bias error
MAE	:	Mean absolute error
BCK	:	Building control knowledge
DRL	:	Deep reinforcement learning
BDQ	:	Branching duelling Q-network
DQN	:	Deep Q-network
LoRa	:	Long Range Networks
ARHMM	:	Auto-regressive hidden Markov model
SVM	:	Support vector machines
ANN	:	Artificial neural networks
CNN	:	Convolution neural networks
CO <sub>2</sub>	:	Carbon dioxide concentration (ppm)
RFID	:	Radio-frequency identification
COTS	:	Commercial of the shelf
PIR	:	Passive infra-red
LSTM	:	Long short-term memory

LHC	:	Lecture hall complex
CHW	:	Chilled water
RA	:	Return air
TFA	:	Treated fresh air units
VFD	:	Variable frequency drive
IAQM	:	Indoor air quality monitor
AI	:	Artificial intelligence
ML	:	Machine learning
VOC	:	Volatile organic compounds
OEM	:	Original equipment manufacturers
SPI	:	Serial peripheral interface
I2C	:	Inter Integrated Circuit
UART	:	Universal asynchronous receiver and transmitter
OLED	:	Organic light emitting diode
LCD	:	Liquid crystalline display
IDE	:	Integrated development environment
CSV	:	Comma separate variable
DF	:	Data frame
SEM	:	Smart energy monitor
ADC	:	Analog to digital converter
NAS	:	Network access server
SN	:	Sensing node
SBC	:	Single board computer
USB	:	Universal serial bus
SSH	:	Secure socket shell

IR	:	Infra-red
RNN	:	Recurrent neural network
EER	:	Energy efficiency ratio
COP	:	Coefficient of performance
DBT	:	Dry bulb temperature (°C)
RH	:	Relative humidity (%)
$P_{\text{sat}}$	:	Saturation pressure corresponding to DBT (kPa)
$P_v$	:	Vapour pressure of water in air (kPa)
w	:	Humidity ratio (kg water/ kg dry air)
h	:	Specific enthalpy (kJ/kg)
p	:	Prediction horizon
$\text{CO}_2_{t+\Delta t}$	:	$\text{CO}_2$ concentration at the next timestep
$\text{CO}_2_t$	:	$\text{CO}_2$ concentration at the current timestep
$O_t$	:	Current occupancy level
G	:	$\text{CO}_2$ generation rate per occupant = 0.0046 lit/s
A	:	The additive co-efficient for occupancy generation rate
B	:	The decay co-efficient for $\text{CO}_2$ levels less than 900 ppm
C	:	Decay co-efficient for $\text{CO}_2$ levels greater than or equal to 900 ppm
$h_{\text{amb}}$	:	Ambient enthalpy (kJ/kg)
$h_{\text{room}}$	:	Room enthalpy (kJ/kg)
HEPA	:	High efficiency particulate arrestance
GI	:	Galvanized iron
NDIR	:	Non-dispersive Infra-red
FDM	:	Fused deposition method

CAD	:	Computer aided design
BLE	:	Bluetooth low energy
MQTT	:	Message queuing telemetry transport
CAP	:	Constrained application protocol
HTTP	:	Hypertext transfer protocol
AMQP	:	Advanced message queuing protocol
API	:	Application program interface
AWS	:	Amazon web services
SDK	:	Software development kit
ALU	:	Arithmetic logical unit
PLC	:	Programmable logic controller
LPWAN	:	Low-power wide area networks