Chemical Engineering Science 192 (2018) 1218–1230

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Synthesis of a quantitative strategy to minimize energy used in conditioning of dry air in buildings in summer with fluctuating ambient and room occupancy rate

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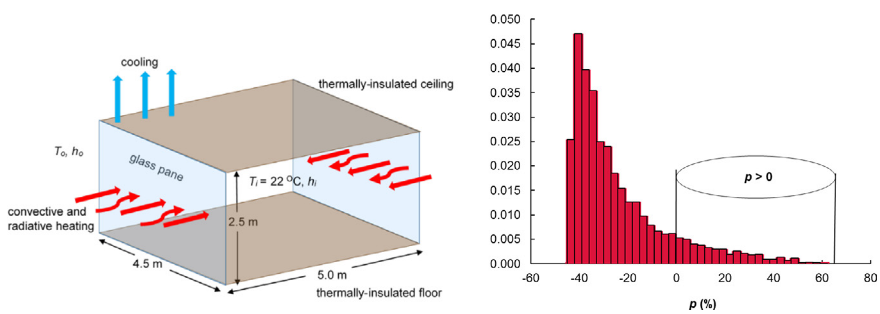
HIGHLIGHTS

- Conditioning of room air in public and commercial buildings important globally.
- Probabilistic *Fr 13* model applicable to fluctuating ambient and occupancy rate.
- *On-only* conditioning strategy economic for commercially viable occupancy rates.
- Reduction in greenhouse gas (GHG) with *on-only* air conditioning strategy.
- Immediate benefit to operators responsible for conditioning of air in summer.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 May 2017
Received in revised form 15 June 2018
Accepted 13 July 2018
Available online 19 July 2018

Keywords:
Conditioning of air in buildings
Energy strategy for air conditioning
Greenhouse gas (GHG) reduction
Probabilistic risk modelling
Fr 13 assessment
Fr 13

ABSTRACT

The conditioning of room air in summer is widely practiced. However many operators do not have an overall quantitative strategy for minimizing energy. Widespread practice is to simply use *on-off*, that is, have air conditioning-on when a room is occupied, and conditioning-off, when un-occupied. Here we apply the probabilistic *Fr 13* risk framework (Chem. Eng. Sci. 152 (2016) 213–226) for the first time to take account of naturally occurring fluctuations in daily ambient peak temperature (T_o), occupancy rates (L_T) and room traffic inflow and outflows (n) in a typical (hotel) room fitted with heat-attenuating curtains in the hot and dry clime of South Eastern Australia (latitude −37.819708, longitude 144.959936). We use this to synthesise an extended steady-state unit-operations model and assess the two energy strategies for conditioning of the room air to a widely used *auto-set* bulk temperature of 22 °C. It was assumed the impact on overall energy demand from room lighting and refrigerator and occupant metabolism was negligible. We show incident radiative energy will be significant, and using historical ambient temperature fluctuations and occupancy rates, that adoption of the alternative *on-only* continuous conditioning would use less energy in 93.6% of summer days, based on an overall commercially viable L_T = 75% with the minimum possible room traffic flow of n = 1. Practically, this equates to six (6) only failures of this alternative energy strategy in the 90 days of summer. Importantly, the probabilistic *Fr 13* framework permits a practical design for larger-scale quantitative testing of the proposed strategy. A preliminary 10-day 'proof-of-concept' trial showed energy savings of 18.9% (AUD $2.23 per suite (paired-room) per day) with a concomitant 20.7% reduction in GHG. Findings will be of immediate interest and benefit to operators and managers of large buildings that rely on conditioning of dry air in summer.

DOI of original article: https://doi.org/10.1016/j.ces.2018.07.038

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https://doi.org/10.1016/j.ces.2018.07.028
0009-2509/

Nomenclature

A	area (m^2) (1)
A_{glass}	surface area of single-glazed glass pane wall (m^2) (7)
A_{brick}	surface area of brick wall (m^2) (8)
c	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$) (15), (19)
d_{glass}	thickness of single-glazed glass pane (0.01 m) (5)
d_{brick}	thickness of brick wall (0.11 m) (6)
D	depth of room (5 m) (8)
g	acceleration constant ($9.81\ m\ s^{-2}$) (14)
Gr	Grashof number (dimensionless) (14)
h	heat transfer coefficient for air ($W\ m^{-2}\ K^{-1}$) (12)
h_o	heat transfer coefficient of outside air ($W\ m^{-2}\ K^{-1}$) (4)
$h_{o,glass}$	heat transfer coefficient of outside air adjacent glass pane ($W\ m^{-2}\ K^{-1}$) (5)
h_i	heat transfer coefficient of inside air ($W\ m^{-2}\ K^{-1}$) (4)
$h_{i,glass}$	heat transfer coefficient of inside air adjacent glass pane ($W\ m^{-2}\ K^{-1}$) (5)
$h_{i,brick}$	heat transfer coefficient of inside air adjacent brick wall ($W\ m^{-2}\ K^{-1}$) (6)
IAC	indoor solar attenuation coefficient (0.8 dimensionless) (25)
k	thermal conductivity of air ($W\ m^{-1}\ K^{-1}$) (4), (20)
k_{glass}	thermal conductivity of glass ($W\ m^{-1}\ K^{-1}$) (5)
k_{brick}	thermal conductivity of brick ($W\ m^{-1}\ K^{-1}$) (6)
L	vertical length (height) of room (2.5 m) (7)
L_T	occupancy rate (days room is let per 100 days, or, h let per 24 h) (%) (27)
n	number of inflows per room (integer ≥ 1) (27)
Nu	Nusselt number (dimensionless) (12)
p	energy strategy risk factor (%) (29)
P	energy strategy risk factor (W) (29a)
Pr	Prandtl number (dimensionless) (12)
$q_{convection}$	convective heat transfer (W) (1)
q_{glass}	convective heat transfer from glass (W) (2)
q_{brick}	convective heat transfer from brick (W) (3)
q^*_{on-off}	heat transfer for *on-off* strategy (W) (26)
q_{on-off}	heat transfer for *on-off* strategy with occupancy rate factor (W) (27)
$q_{on-only}$	heat transfer for *on-only* strategy (W) (28)
$q^*_{radiation}$	radiative heat transfer (W) (24)
$q_{radiation}$	radiative heat transfer through the glass pane wall (W) (25)
R^2	correlation coefficient (dimensionless)
Ra	Rayleigh number (dimensionless) (12)
ΔT	temperature difference between outside and inside of room (K or °C) (1)
$\delta T_{o,glass}$	temperature difference between glass wall and air film outside of room (°C) (21)
$\delta T_{i,glass}$	temperature difference between glass wall and air film inside of room (°C) (22)
δT_{brick}	temperature gradient between brick wall and interior of room (°C) (23)
T	temperature (K) (°C + 273.15) (16)
$T_{air,glass}$	average film temperature on glass pane (K) (10)
$T_{air,brick}$	average film temperature on brick wall (K) (11)
T_{brick}	average temperature of brick wall (K) (11)
T_i	*auto-set* bulk temperature of room interior air (K) (9)
T_o	ambient bulk temperature (outside air) (K) (9)
U_o	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) (1)
$U_{o,glass}$	overall heat transfer coefficient of glass ($W\ m^{-2}\ K^{-1}$) (4)
$U_{o,brick}$	overall heat transfer coefficient of brick ($W\ m^{-2}\ K^{-1}$) (5)
W	width of room (4.5 m) (7)

Greek

α	shape factor for Betageneral distribution
β	volumetric βcoefficient of expansion of air (K^{-1}) (16)
ε	emissivity of glass (0.8 dimensionless) (24)
Δ	difference between two parameter values (1)
ρ	density of air ($kg\ m^{-3}$) (14), (17)
μ	dynamic viscosity of air ($N\ s\ m^{-2}$) (14), (18)
σ	Stefan-Boltzmann constant ($5.667 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$) (24)

Subscripts

air	air film
brick	brick wall
glass	vertical glass pane
i	inside (interior)
o	outside (ambient)

Other

auto-set	room set-point for bulk air temperature (22 °C)
control	suite with *on-off* conditioning practice
GHG	greenhouse gas
on-off	energy strategy for air conditioning switched-on by occupant inflow
on-only	energy strategy for air conditioning on-continuously
SHG	solar heat gain – function of glass and solar radiation distribution
treated	suite with alternative *on-only* conditioning practice

(The number in parentheses after description refers to the equation(s) in which the symbol is first used or defined.)

1. Introduction

Many buildings, including public structures and commercial hotels, commonly have a concrete-and-steel frame to provide strength, together with exterior walls of glass known as curtain walls (Anon., 2013) to provide daylight to the interior. In summer these glass walls allow solar heat gain (SHG) from ambient to the interior (and conversely, heat loss in winter). The problem is acute on extreme temperature days. As a consequence, air conditioning systems are installed so that the room interior air is conditioned and maintained at a design *auto-set* temperature during summer (Tom, 2008), customarily at a bulk room temperature of 22 °C.

With respect to existing literature on building environmental control, work has generally focused on the design, calibration, measurement and modelling of air flow together with management of air conditioning systems using discrete and deterministic assessments (Coakley et al., 2012; Martani et al., 2012; Eisenhower et al., 2012; Horikiri et al., 2014) or tactics (Oldewurtel et al., 2012; Ma et al., 2012; Glicksman and Taub, 1997) and, not on mathematically rigorous developments for a quantitative energy strategy for the overall design and management of multi-room buildings to minimise energy use and costs.

In summer an industry default strategy that is widely believed to limit conditioning energy and costs, and almost universally practiced, is to manually switch-on the air conditioning when a room is occupied and manually switch-off immediately the room is unoccupied. This is referred to as the *on-off* strategy – this is especially true, for example, in multi-room hotels and government and public buildings. An alternative however is to leave the air conditioning continuously on, the *on-only* strategy irrespective of