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The effects of interior emissivity and room layout on forced air space-conditioning power usage

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ABSTRACT

Through computational fluid dynamics studies, this paper analyzes the effects of and interactions between interior surface emissivity, positioning of forced-air supply/return locations, and building "tightness" on space-conditioning power requirements in a simple model room. Each is shown to be important, but all are highly interdependent. In well-sealed rooms, layout is shown to be largely unimportant and extremely low-emissivity ($\varepsilon = 0.1$) a slight (2–5%) benefit. With high infiltration or external ventilation requirements, poor supply/return locations can increase power usage twofold, and extremely low emissivity produces a $\pm 20\%$ change in power-consumption depending on the room layout.

1. Introduction

Energy use in residential and commercial buildings accounts for up to 40% of primary energy consumption depending on climate region, and of that fraction, 40–60% is used on space conditioning [1]. While the development of more energy efficient equipment and building materials as well as ever improving building codes and equipment standards have reduced the energy required to condition per unit area over time, there has not been a commensurate reduction in building energy consumption [1,2]. This has been blamed on the construction of larger spaces, wider use of air-conditioning, lack of attention to systems integration, and increased adoption of miscellaneous electrical loads. Further, despite typically low payback periods for energy efficient building retrofits, various barriers oftentimes impede building owners from proceeding along the most energy efficient path [3]. This resistance creates an environment in which low-cost, low-labor products and practices with perceived energy-savings benefits can thrive in the marketplace. Some, like thermostat adjustment, weather-stripping, caulking, etc., are effective at reducing energy use outright [4], while others like fans can save energy indirectly in the summer by raising occupant tolerance for higher temperatures [5–7]. Among the inexpensive possibilities for energy savings, "insulating paints" and "radiant barrier paints" have been proposed. These products' manufacturers claim a wide range of efficiency gains by simply coating walls with specially formulated paint. While some of these products can be largely discredited by simple analysis, those whose claimed effect is on *radiative* properties on the interior of a structure warrant closer analysis.

Through computational fluid dynamics (CFD) simulations, this paper examines the effects of interior surface emissivity on overall space-conditioning power for forced-air heated/cooled test-spaces in a variety of room configurations. By analyzing various room arrangements with different emissivities, the relationships between placement of air sources/sinks, interior temperature distributions, energy use, and interior-facing emissivities are examined and understood. Additionally, insight to the influence of space conditioning inlet/outlet locations within a room without specialized paints is provided.

1.1. Energy savings from interior radiative effects

Potential energy-saving effects from manipulation of radiative heat transfer have been well analyzed with regard to windows [8,9], "radiant barriers" for attics [10–12], reflective films on layers of general insulation [13,14], and solar effects of "cool" exterior surfaces [15,16]. However, radiant properties of fully interior surfaces have received only limited in-depth investigation. Since these interior surfaces have the potential to affect both the interior temperature distribution *and* envelope heat transfer in non-trivial ways, their analysis is more nuanced. While typical interior coatings have overall emissivities ≈ 0.9 (regardless of color) [17],

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certain specialized coatings with aluminum-flakes, for example, can achieve emissivities as low as 0.25 [18]. Ceramic additives also exist that can reduce the emissivity of standard paints by 5–10% [19].

Beck et al. [20] analyzed the effects of reflective shields on the efficiency of "radiator" heating, finding that a black backing on walls behind the installations resulted in a 5–10% increase in heat transfer to the room over a reflective surface due to increased convection in the air space between the radiator and wall. Le Dreau et al. [21] considered the influence of floor emissivity on the effectiveness of nighttime "displacement ventilation" cooling systems in which thermal stratification is leveraged to condition spaces (most frequently, offices) with a low-velocity supply of moderately chilled air. Their work indicated that a dramatic drop in floor emissivity (from 0.73 to 0.03) had little influence on the overall system effectiveness, albeit in a highly specific case. Joudi et al. [18] used an experimental 13 m^2 cabin to analyze the energy-saving potential of highly reflective exterior and interior surfaces in a Swedish climate, finding that for their particular scenarios ("design day" cooling; electric-floor heating), there was definite cooling benefit (about 10%) and probable minor heating benefit to both-side reflective cabin surfaces. Later in [22], those tests are expanded, finding that the overall benefits of reflective surface cladding varied positively with ventilation rates, negatively with internal loads, and insignificantly with size (i.e. ratio of reflective area to volume). Results in both papers [18,22] were explained (and sometimes predicted) by "well-mixed" models. Examinations of interior emissivities seem confined to highly specialized cases, or leave open the possibility of neglected secondary but significant effects.

1.2. Building simulation and room layouts

Computational models used to explore heat and mass transport in buildings can vary wildly in complexity. While modeling systems such as EnergyPlus oftentimes provide the necessary complexity at a system level, they are typically limited to a number of "well-mixed" zones in which thermal properties are uniform [23]. Missing from these system-level simulations are direct insight into the influences of air motion, temperature stratification, and varied internal properties. CFD analyses provide this level of detail, but require immense and oftentimes impractical computational time, complexity, and expertise of the modeler [24]. Methods [25,26], performance [27], and applicability [28] of coupling the two approaches have been addressed in a number of published works, but the need for intelligent compromise between accuracy and computational expense makes building-simulation tools that integrate CFD by default exceedingly rare [24]. Despite the expense, CFD is still frequently employed to directly isolate and analyze effects that would be lost in well-mixed models; for example, thermal comfort and energy-use effects relating to arrangements of forced-air supply locations [29], combined methods of space conditioning [30], and buoyancy-driven, non-energy-intensive conditioning [31,32]. Gao and Lee [29] modeled and validated the effects of air-conditioning inlet placement on residential occupant comfort a small (13 m^2) room with light furniture, demonstrating that proper inlet placement can improve comfort and reduce energy usage. Chiang et al. [30] examined the effectiveness of radiant cooling in an office setting under various configurations using CFD, concluding that for their examined climate zone, radiant ceiling panels combined with low velocity, slightly chilled forced air would provide less energy-intensive (roughly 8%) climate control than forced air alone. Displacement ventilation – leveraging buoyant temperature-stratification to provide cooling with relatively warm, low-velocity air – relies entirely on effects that would be lost in well-mixed models. The choice of inlet and exhaust placement [32] and supply temperature [31] are both critical to the performance of such systems in terms of occupant comfort and indoor air quality. Particularly in [32], the inlet locations are shown to be highly critical to satisfactory performance of such systems. CFD has also been used for extremely large spaces with complex airflow patterns and distribution of heat loads where system arrangements are highly critical, as done by Li et al. [33], who evaluated alternate systems of cooling a train station. Even extremely complicated scenarios such as combined indoor/outdoor CFD modeling for natural ventilation have been successfully modeled [34]. In short, careful use of CFD modeling is an established and accurate way to evaluate thermal behavior that would be lost in well-mixed, system-level simulations that cannot capture subtle but important effects, and internal room arrangements are frequently shown to be critical to performance of space-conditioning systems of all kinds.

2. Description of model and tests

2.1. Model

CFD simulations were performed using ANSYS FLUENT on an empty, square structure with four exterior walls, i.e. a "cabin in the woods". Details of input information are presented in Tables 1 and 2 while Fig. 1 shows a dimensioned overhead view of the room. To save unnecessary computational expense, only one symmetric eighth of the room was modeled; this region is outlined. As in Fig. 1, each wall length was set to 3.048 m (10 ft), and the walls and ceiling were modeled as slab regions 0.25 m thick. A square air supply inlet, 0.2 m on a side, was placed in the center of the room to mimic a forced air heating/cooling system supply. Four air exhaust outlets, each with a quarter of the area of the inlet, were placed 1.1 m from the center of the room on each of the room's major axes. Placement of inlets/outlets on the floor or ceiling is discussed later, but the overhead view remains the same in all configurations. These exhaust outlets can be thought of as either the location of return air registers and/or an aggregate of the leaks in

Table 1
Exterior boundary conditions of heating and cooling simulations for convective and radiative modes of heat transfer. For convection, h is a convective heat-transfer coefficient and T_∞ is a free-stream temperature. For radiation, ε is the surface emissivity, and T_{surr} is the temperature of the surroundings. For cooling simulations, the exterior temperature of the roof is taken as a worst-case constant [35].

External boundary		Parameter
Case	Heat transfer mode	
Heating	Convection	$h = 20\ W\ m^{-2}\ K^{-1}$ $T_\infty = -8\ °C$
	Radiation	$\varepsilon = 0.9$ $T_{surr} = -8\ °C$
Cooling	Convection (walls)	$h = 20\ W\ m^{-2}\ K^{-1}$ $T_\infty = 28\ °C$
	Radiation (walls)	$\varepsilon = 0.9$ $T_{surr} = 28\ °C$
	Roof	$T = 74\ °C$

Table 2
Interior temperatures for heating and cooling simulations. Inlet temperatures are specified as known boundary conditions. The "Room (Goal)" temperature is the desired steady-state volumetric average for the room.

Case	Temperature (°C)	
Heating	Inlet	43
	Room (Goal)	20
Cooling	Inlet	11
	Room (Goal)	22