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Effects of airflow infiltration on the thermal performance of internally insulated ducts

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Abstract

Air flowing through a supply duct infiltrates perviously faced, porous, internal duct insulation, degrading its thermal performance. Encapsulating the insulation's air-facing surface with an impervious barrier prevents infiltration, increasing the capacity of the conditioned supply air to heat or cool the space to which it is delivered.

This study determined the air-speed dependence of the thermal conductivity of fiberglass insulation by measuring the inlet-to-outlet temperature drop of heated air flowing through a long, insulated flexible duct. The conductivity of a flexible duct's low-density, internal, fiberglass-blanket insulation increased with the square of the duct air speed, rising by 140% as the duct air speed increased from 0 to 15 $\mathrm{m\ s^{-1}}$. At air speeds recommended for branch ducts, the conductivity of such insulation would increase by 6% above its still-air value in a residential system and by 16% in a commercial system. Results partially agreed with those reported by an earlier study.

Simulations indicate that encapsulating the air-stream surface of internal fiberglass duct insulation with an impervious barrier increases the effectiveness with which a duct delivers the thermal capacity of supply air by 0.15%–0.9% in typical duct systems. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Airflow infiltration; Thermal performance; Internal-duct insulation

1. Introduction

1.1. Duct system heat gains and losses

Heat gains and losses to duct systems in residential and commercial buildings have been shown to strongly influence the energy efficiency with which conditioned air is delivered to the occupied space. Based both on measurement and simulation, Palmiter and Francisco [5] estimated that heat pump systems in the Pacific Northwest might suffer a 10% increase in seasonal energy requirements from conduction losses from ducts located in crawlspaces. In a very different climate, Parker et al. [6] predicted through a detailed simulation that peak residential duct system heat gains could approach 33% of available cooling system capacity under peak conditions when ducts were located in an attic. Jump et al. [2] performed detailed measurements that determined that supply-duct conduction reduced residential space conditioning efficiency by 16% in California homes tested.

1.2. Delivery effectiveness of a supply air duct

A supply air duct may contain a fiberglass lining for acoustic control and thermal insulation. As conditioned air travels through a supply duct, heat exchange between the air and the duct's surroundings reduces the air's "thermal capacity," or rate at which it can heat or cool the space to which it is delivered. The magnitude of this thermal gain or loss is inversely proportional to the duct's total thermal resistance, which is the sum of the resistance of the duct's insulated wall and the resistances of the boundary-layer air films inside and outside the duct's wall. Increasing the resistance of the duct's insulation will reduce the thermal gain or loss from the duct, and thereby raise the fraction of the supply air's inlet thermal capacity delivered to the duct's outlet. This ratio of outlet capacity to inlet capacity is the duct's "delivery effectiveness."

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1.3. Increasing effectiveness by preventing infiltration

Air flowing through a duct will infiltrate internal fiberglass insulation if the insulation's air-facing surface is pervious. Infiltration induces forced convection within the fiberglass, raising its effective thermal conductivity and lowering its thermal resistance. Encapsulating the insulation's air-facing surface with an impervious barrier prevents infiltration of the insulation and degradation of its thermal performance.

The increase in delivery effectiveness induced by encapsulating the insulation's surface is the duct's "effectiveness gain." Given the variation with air speed of its insulation's conductivity, a duct's effectiveness gain can be calculated for arbitrary duct geometries, duct air speeds, and exterior ambient conditions.

1.4. Reported measurement of the change in total thermal resistance due to infiltration

Only one report of the variation with duct air speed of the total resistance of fiberglass-insulated ductwork was found in the literature. Lauvray [3] reported that the total conductance of a flexible duct with internal fiberglass insulation was invariant at air speeds below 5 m s^{-1}, and rose linearly with air speed at speeds above 5 m s^{-1}. The study did not report the diameter of the duct, the thickness of its insulation, the emissivity of its outer surface, or the speed and temperature of the ambient air. Thus, it is difficult to generalize the reported variation of total thermal resistance, or to calculate the variation with air speed of the insulation's thermal conductivity. No reports of the variation with duct air speed of the conductivity of internal fiberglass insulation were found.

1.5. Elements of current study

This study determined the air-speed dependence of the conductivity of fiberglass insulation by measuring the inlet-to-outlet temperature drop of heated air as it traveled at various speeds through a long, insulated flexible duct. The results were used to simulate the effectiveness gains obtainable by encapsulating the air-facing surface of the insulation inside ducts in residential and commercial systems. The simulations modeled flexible and rigid ducts, hot and cold air supplies, and duct locations inside and outside the building's thermal envelope.

The temperature-drop conductivity measurement technique requires a long, narrow duct to obtain a good ratio of signal to noise in the observed temperature difference. Flexible branch ducts are manufactured in lengths of up to 15 m, and are typically insulated with low-density fiberglass blankets. Rigid main ducts — e.g., rectangular sheet-metal trunk ducts — are typically insulated with high-density fiberglass blankets, and are not usually manufactured in long lengths. The high-density blankets are less permeable to air than are low-density blankets, and their conductivities are expected to vary less with duct air speed.

Since it was more convenient to obtain a long run of insulated flexible duct than a long run of insulated rigid duct, the conductivity measurements were performed on low-density, flexible-duct insulation. The permeabilities of the low- and high-density blankets were measured, and their ratio used to theoretically extrapolate the air-speed variation of the conductivity of the high-density, rigid-duct insulation from that measured for the low-density blanket.

2. Theory

2.1. Effect of thermal losses from duct on thermal capacity of supply air

2.1.1. Thermal capacity

To maintain the air in a conditioned room at constant temperature and humidity, the net influx of enthalpy from the inflow of supply air and outflow of room air must equal the room's net thermal load. If the room's airflow is balanced, this net enthalpy influx is the supply air's thermal capacity,

$$C \equiv \dot{m}_a (H - H_R). \tag{1}$$

Here $\dot{m}_a$ is the mass flow rate of the dry-air component of the supply air, and H and H_R are the enthalpies/unit mass dry air of the supply air and room air, respectively.

2.1.2. Delivery effectiveness

The effectiveness with which a duct delivers capacity is defined as the ratio of the capacity at its outlet, C_B, to the capacity at its inlet, C_A. If the duct is airtight and free of internal condensation, its delivery effectiveness is

$$\varepsilon_C \equiv \frac{C_B}{C_A} = 1 - \frac{c_p (T_A - T_B)}{H_A - H_R}, \tag{2}$$

where T_A and T_B are the temperatures at inlet and outlet, and c_p is the air's specific heat/unit mass.

2.1.3. Influence of thermal resistance on delivery effectiveness

The duct's delivery effectiveness is related by an energy balance to its "total resistance," R, or resistance to heat transfer from the air in the duct to the duct's surroundings:

$$\varepsilon_C = 1 - \frac{c_p [1 - \exp(-\Re/R)] (T_A - T_\infty)}{H_A - H_R}, \tag{3}$$

where T_∞ is the temperature of the duct's surroundings, $\Re = 4l/(\rho_a c_p v d_{h,i})$ is a characteristic thermal resistance, l is the length of the duct, ρ_a is the density of dry air, v is the bulk velocity of airflow through the duct, $d_{h,i} \equiv 4 A_i / P_i$ is the duct's inner hydraulic diameter, A_i is the duct's inner cross-sectional area, and P_i is the duct's inner perimeter [5]. Increasing the duct's total resistance from R to R' will increase its delivery effectiveness by

$$\Delta \varepsilon_C \equiv \varepsilon_C(R') - \varepsilon_C(R). \tag{4}$$

This rise in effectiveness is denoted the duct's effectiveness gain.

2.2. Variation of the effective thermal conductivity of fiberglass insulation with temperature and duct air speed

2.2.1. Variation of total resistance with insulation's effective thermal conductivity

The total resistance R of a fiberglass-insulated duct is the sum of the inner air film resistance R_i, the insulation resistance R_f, and the outer air film resistance R_o. The thickness and resistance of the duct wall are each at least an order of magnitude smaller than those of the fiberglass insulation, and may be neglected in the thermal analysis.

The insulation's resistance is inversely proportional to its effective thermal conductivity, k_f. Thus, lowering the insulation's effective thermal conductivity (or "conductivity," for short) will increase the insulation's resistance, the duct's total resistance, and the duct's delivery effectiveness.

2.2.2. Variation with temperature and duct air speed of insulation conductivity

The conductivity of infiltrated internal fiberglass duct insulation varies with both fiberglass temperature and duct air speed. Over the temperature range of interest to HVAC applications — say, 0°C to 50°C — the conductivity of fiberglass increases approximately linearly with its mean temperature $\overline{T}_f$. Theory [5] and measurements developed in this study indicate that the conductivity of infiltrated insulation increases linearly with the square of the duct air speed. Thus, if the conductivity varies independently with temperature and duct air speed,

$$k_f(\overline{T}_f, v) = k_{f0}^*\left[1 + \gamma_T(\overline{T}_f - T^*)\right]\left[1 + \gamma_v v^2\right], \tag{5}$$

where γ_T and γ_v are the sensitivities of the insulation's effective thermal conductivity to temperature and velocity, and k_{f0}^* is the still-air conductivity of fiberglass insulation at reference mean temperature $T^* = 24$°C.

2.2.3. Variation with permeability of velocity sensitivity

The permeability to a fluid of a porous medium is the ratio of the fluid's bulk-flow velocity through the medium to the magnitude of the pressure gradient across the medium. Flow analysis suggests that the velocity sensitivity γ_v of a porous insulator is proportional to its permeability to air [5].

2.3. Increasing effectiveness by preventing infiltration of internal fiberglass duct insulation

2.3.1. Encapsulating insulation to prevent degradation of thermal resistance

Consider a perviously faced fiberglass blanket of still-air conductivity k_{f0}. When it is installed inside a duct, air flowing through the duct can infiltrate the fiberglass, inducing forced convection within the insulation that increases its conductivity to some value $k_f(v) > k_{f0}$ Encapsulating the air-facing surface of the insulation with an impervious barrier will prevent infiltration, lowering the insulation's conductivity at a given duct air speed from $k_f = k_f(v)$ to $k'_f = k_{f0}$. Encapsulation thereby increases both the insulation resistance and the total resistance by

$$\begin{aligned}\Delta R = \Delta R_f &= r_i \ln(r_o/r_i)(1/k'_f - 1/k_f)\\ &= \frac{r_i \ln(r_o/r_i)}{k_{f0}}\left[\frac{\gamma_v v^2}{1 + \gamma_v v^2}\right],\end{aligned} \tag{6}$$

where r_i and r_o are the duct's inner and outer radii, respectively. The effectiveness gain is given by Eq. (4), where $R' = R + \Delta R$.

2.3.2. Parameters influencing magnitude of effectiveness gain

When the magnitude of the inlet-to-outlet temperature difference is much smaller than the magnitude of the temperature difference between the duct air and the duct's surroundings, the effectiveness gain is approximately

$$\Delta\varepsilon_C \approx -\frac{4l(T_A - T_\infty)\Delta U}{\rho_a d_{h,i} v (H_A - H_R)}, \tag{7}$$

where $U = 1/R$ is the duct's total thermal conductance, and $\Delta U = U' - U$ is the change in total conductance induced by encapsulation. The approximate effectiveness gain is proportional to both the duct length l and the inlet-to-ambient temperature difference $(T_A - T_\infty)$, and inversely proportional to both the duct's inner hydraulic diameter $d_{h,i}$ and the inlet-to-room enthalpy difference $(H_A - H_R)$ [5].

2.4. Determining sensitivity of effective thermal conductivity to duct air speed

An energy balance relates the duct's total thermal resistance R to measured values of its inlet, outlet, and ambient air temperatures. The insulation's thermal resistance can be found by subtracting the air film resistances from the total resistance. Then, the insulation's conductivity can be calculated from the insulation's resistance [4]. Since the variation with temperature of the conductivity of fiberglass is known [1, p. 24.18], the velocity sensitivity γ_v and the still-air reference-temperature conductivity $k_f{}^*{}_0$, of the insulation can be determined by measuring $k_f^*(v)$ over a range of air speeds, then regressing a function of the form of Eq. (5) to the data.

3. Experimental measurement of the conductivity of fiberglass insulation vs. duct air speed

3.1. Overview

The total resistance of a long, flexible duct with internal fiberglass insulation was measured by blowing hot air through the duct at various speeds, then measuring the air's bulk velocity and the steady-state values of the duct inlet, duct outlet, and ambient air temperatures. These data were used to compute (a) the duct's total resistance R and (b) the insulation's resistance R_f, conductivity k_f, reference-temperature conductivity k_f^*, still-air reference-temperature conductivity k_{f0}^*, and velocity sensitivity γ_v. The conductivities of both perviously and imperviously faced fiberglass blankets were measured with the expectation that the former would vary with air speed, while the latter would remain constant.

3.2. Experiment

Air was heated to temperatures ranging from 32°C–47°C, then blown at bulk speeds of 1–16 m s^{-1} into a 15-m length of fiberglass-insulated flexible duct. The duct's inner and outer diameters were 15 and 21 cm, respectively. The duct rested on a carpeted floor, and was pulled taut in a U-configuration (Fig. 1).

Steady-state values of the duct's inlet air temperature and inlet-to-outlet air temperature differential were measured with a pair of resistance temperature detection (RTD) probes (differential mode accuracy ±0.03°C). Temperatures were considered steady when, after a period of 20–60 min, the fluctuation in temperature difference fell to 0.1°C.

The inlet and outlet temperatures were measured along the duct's centerline, approximately 10 inner diameters (1.5 m) inwards of the duct's ends. The inlet-to-outlet drop in air temperature ranged from 0.3°C–5.4°C, varying with the inlet air temperature and duct air speed. The ambient air temperature and velocity were measured with a hot wire anemometer (accuracy ±0.3°C, ±0.1 m s^{-1}), and ranged from 21°C–26°C and 0.0–0.1 m s^{-1}, respectively. The volumetric flow rate through the system was measured with an orifice-type flow meter (accuracy ±5%) built into the heater/fan unit.

Separate trials were conducted with fabric-core and plastic-core fiberglass-insulated flexible ducts. Each duct consisted of a 15-cm diameter spring-wire helix frame encapsulated in a thin inner core of either non-woven fabric (thickness 10^{-1} mm, flat-form thermal resistance 10^{-2} m^2 K W^{-1}) or plastic (thickness 10^{-1} mm, flat-form thermal resistance 10^{-3} m^2 K W^{-1}). The inner core was surrounded by a low-density fiberglass blanket (thickness 2.9 cm, density 13 kg m^{-3}, flat-form nominal thermal resistance 0.74 m^2 K W^{-1} [4.2 h ft^2 F Btu^{-1}]), which was in turn encapsulated in a metalized plastic jacket (thickness 10^{-1} mm, flat-form thermal resistance 10^{-3} m^2 K W^{-1}, outer-surface long-wave emissivity 0.47). The duct's inner core acted as the blanket's air-facing surface.

The permeability to air of a high-density fiberglass blanket used to line rigid ducts (thickness 2.5 cm, density 24 kg m^{-3}, flat-form nominal thermal resistance 0.63 m^2 K W^{-1} [3.6 h ft^2 F Btu^{-1}]) was measured to be approximately half that of the low-density blanket in the flexible duct [4].

3.3. Results

3.3.1. Variation of conductivity with duct air speed

The reference-temperature conductivity of the imperviously faced blanket was approximately constant, with a 95% confidence-level value of $k_f^* = 0.037 \pm 0.002$ W m^{-1} K^{-1}. The reference-temperature conductivity of the pervi-

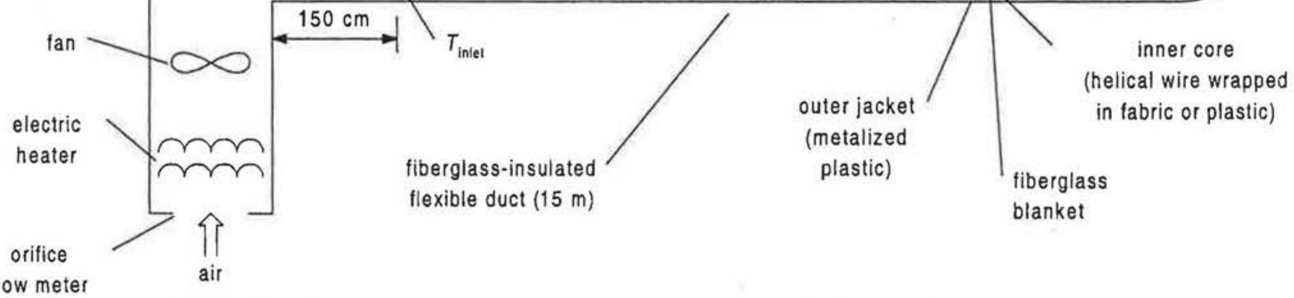

Fig. 1. Heater, fan, and insulated flexible duct used to measure the effect of infiltration on the effective thermal conductivity of fiberglass duct insulation.

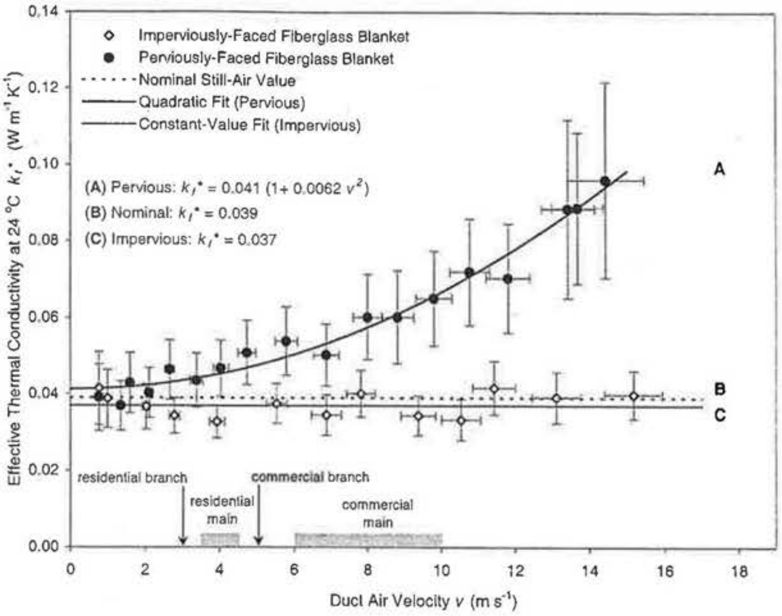

Fig. 2. Variation with duct air speed of the effective thermal conductivity at 24°C of perviously and imperviously faced fiberglass blankets (density 13 kg m^{-3}) in flexible ducts. Also shown is the nominal, still-air effective thermal conductivity for both blankets.

ously faced fiberglass blanket rose with the square of the duct air speed in the fashion of Eq. (5). The 95% confidence-level regressed values of its still-air, reference-temperature conductivity and its velocity sensitivity were $k_f{}^*{}_0 = 0.041 \pm 0.002$ W m^{-1} K^{-1} and $\gamma_v = 0.0062 \pm 0.0005$ s^2 m^{-2} (Fig. 2).

The regressed reference-temperature, still-air conductivities of the imperviously and perviously faced blankets were within 5% of the blankets' nominal conductivity value of 0.039 W m^{-1} K^{-1}.

The increase in the conductivity of the flexible duct's perviously faced, low-density fiberglass blanket is shown

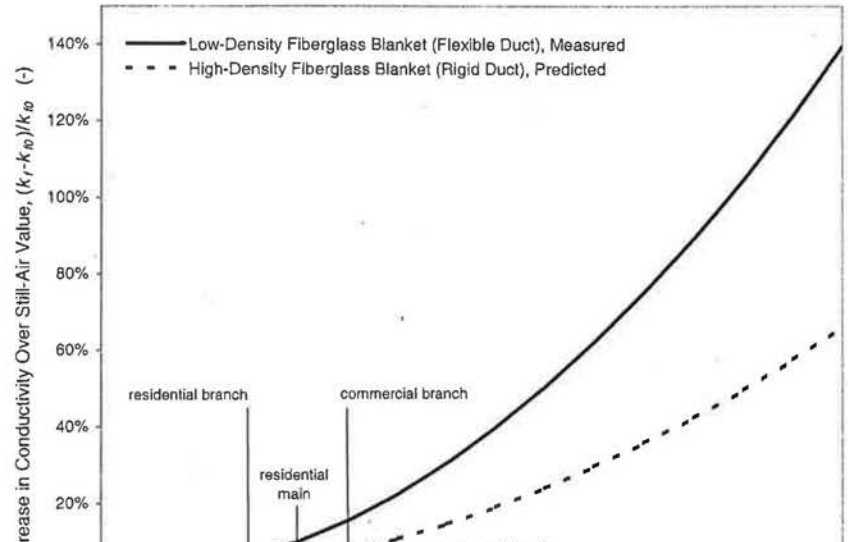

Fig. 3. Variation with duct air speed of the infiltration-induced fractional increase of the conductivities of low-density (13 kg m^{-3}) and high-density (24 kg m^{-3}) fiberglass blankets. The low-density blanket's conductivity was measured, while the high-density blanket's conductivity was extrapolated from that of the low-density blanket's result by assuming that the sensitivity of conductivity to air speed is proportional to permeability.

Table 1
Duct air speeds recommended to minimize flow noise [7, p. 6.4]

Duct air speed ($m\ s^{-1}$)	Residential	Commercial
Branch duct	3	5
Main duct	3.5–4.5	6–10

Table 2
Fractional increases due to infiltration of the conductivities of fiberglass insulation in flexible branch ducts and rigid main ducts in residential and commercial systems, computed for the duct air speeds recommended to minimize noise

Conductivity increase due to infiltration (%)	Residential	Commercial
Flexible branch duct	6	16
Rigid main duct	4–6	11–29

as a percentage of its still-air conductivity in Fig. 3. Also shown is the conductivity increase with air speed for a high-density, rigid-duct fiberglass blanket, which has been extrapolated from that of the low-density-blanket by assuming that velocity sensitivity is proportional to permeability.

Table 1 shows air speeds recommended to minimize flow noise in main ducts and branch ducts in residential and commercial systems [7, p. 6.4]. Flexible ductwork is used for branch ducts, while rigid ductwork is used for main ducts. Typical increases in the conductivities of flexible branch-duct insulation and rigid main-duct insulation in residential and commercial systems are presented in Table 2.

3.3.2. Variation of total conductance with air speed

The total conductance of the pervious-core flexible duct increased approximately linearly with air speed, rising from its still-air value of 0.85 $W\ m^{-2}\ K^{-1}$ by 10% per 1 $m\ s^{-1}$ increase in velocity (Fig. 4). This partly agrees with the results reported by Lauvray [3], who found that the total conductance of a pervious-core flexible duct retained its still-air value for air speeds below 5 $m\ s^{-1}$, but rose by 16% per 1 $m\ s^{-1}$ increase in duct air velocity above 5 $m\ s^{-1}$.

The total thermal conductance of the impervious-core flexible duct increased approximately linearly with air speed, rising from its still-air value of 1.0 $W\ m^{-2}\ K^{-1}$ by 2% per 1 $m\ s^{-1}$ increase in velocity. This slight increase in total conductance with air speed results from the decrease in the resistance of the inner air film.

The projected zero-velocity total conductances of the pervious- and impervious-core flexible ducts were equal to within 5%.

4. Simulated effectiveness gains of typical supply ducts

4.1. Overview

The gain in delivery effectiveness achieved by encapsulating the pervious air-facing surface of a supply duct's internal fiberglass insulation depends on

(a) duct properties (length, cross-section, and outer surface's long-wave emissivity);

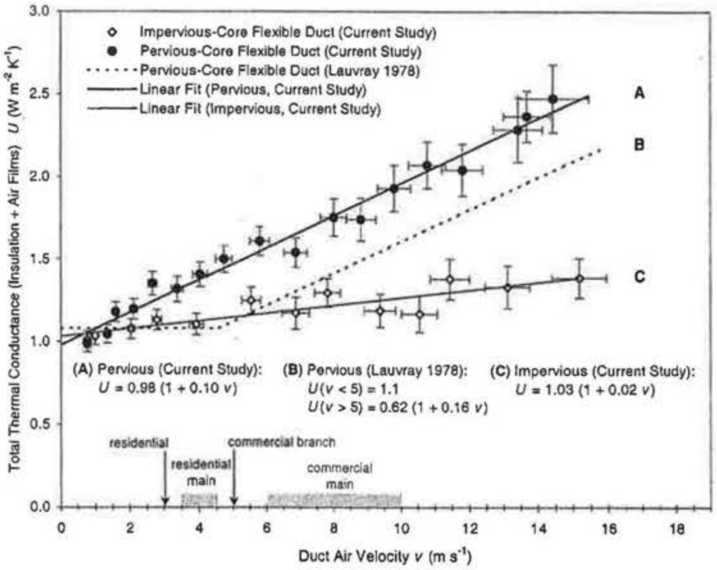

Fig. 4. Variation with duct air speed of the total thermal conductance (fiberglass plus air films) of insulated flexible ducts with pervious and impervious inner cores. The ducts have an inner diameter of 15 cm (6.0 in.), internal fiberglass insulation (thickness 2.9 cm, density 13 $kg\ m^{-3}$, flat-form nominal thermal resistance 0.74 $m^2\ K\ W^{-1}$ [4.2 $h\ ft^2\ F\ Btu^{-1}$]), and a metalized plastic outer jacket (long-wave emissivity 0.47). Also shown is the total thermal conductance reported by Lauvray [3] for a pervious-core flexible duct (nominal flat-form resistance of fiberglass insulation, 0.77 $m^2\ K\ W^{-1}$ [4.3 $h\ ft^2\ F\ Btu^{-1}$]; no other information reported).

Table 3
Properties of modeled flexible and rigid ducts

	Flexible branch duct	Rigid main duct
Length (m)	7.5	30
Inner diameter (cm)	20	–
Outer height and width (cm)	–	30×91
Outer-surface long-wave emissivity (–)	0.9	0.2
Insulation density (kg m^{-3})	13	24
Insulation thickness (cm)	2.9	2.5
Insulation's nominal flat-form, still-air thermal resistance (m^2 K W^{-1})	0.74	0.63
Velocity sensitivity of insulation conductivity (s^2 m^{-2})	0.0062	0.0029
Temperature sensitivity of insulation conductivity (K^{-1})	0.0047	0.0018

(b) insulation properties (thickness, still-air conductivity, and sensitivities of conductivity to temperature and velocity);
(c) duct-exterior conditions (air temperature and velocity);
(d) inlet-air conditions (temperature and humidity); and
(e) room-air conditions (temperature and humidity).

4.2. Scenarios modeled

Effectiveness gain vs. air speed was simulated for eight combinations of supply-duct type, supply-air temperature, and supply-duct location:

$$\left\{\begin{array}{c}\text{flexible duct}\\ \text{OR}\\ \text{rigid duct}\end{array}\right\} \times \left\{\begin{array}{c}\text{hot supply air}\\ \text{OR}\\ \text{cold supply air}\end{array}\right\}$$

$$\times \left\{\begin{array}{c}\text{duct inside thermal envelope}\\ \text{OR}\\ \text{duct outside thermal envelope}\end{array}\right\}.$$

4.2.1. Ducts

Supply air is usually transmitted over short distances with flexible branch ducts, and over long distances with rigid main ducts. The first duct modeled was a 7.5-m long, 20-cm inner diameter, pervious-core flexible branch duct, internally insulated with a low-density fiberglass blanket. The second was a 30-m long, 30×21 cm outer cross-section, galvanized-steel, rigid main duct, internally insulated with a high-density fiberglass blanket (Table 3).

4.2.2. Inlet and outlet conditions

Supply ducts may deliver either hot or cold air to a conditioned room. Hot and cold plenum air temperatures and humidities were chosen to represent typical HVAC operating conditions, while the room air temperatures and humidities were chosen to lie within the human comfort zone [1, p. 8.12].

4.2.3. Ambient conditions

If a supply duct is located within the room's thermal envelope — e.g., in a ceiling space that serves as a return plenum — heat from light fixtures may raise the duct's ambient air temperature several degrees Celsius above room air temperature. If the supply duct lies outside the room's thermal envelope, its ambient air temperature may be close to the outside air temperature (Table 4).

4.3. Results

Effectiveness gains increased with duct air speed in all eight scenarios (Figs. 5 and 6). Effectiveness gains for flexible branch ducts and rigid main ducts at air speeds recommended for residential and commercial systems are summarized in Table 5. Gains in commercial systems were approximately twice those of residential systems, because the former operate at higher duct air velocities.

As predicted by Eq. (7), effectiveness gains were higher for ducts outside the thermal envelope than for ducts inside the thermal envelope, because the magnitude of the temperature difference between the supply air and the ambient

Table 4
Plenum, room, and ambient air conditions for heating and cooling ducts inside and outside of the room's thermal envelope

	Cooling duct inside thermal envelope	Cooling duct outside thermal envelope	Heating duct inside thermal envelope	Heating duct outside thermal envelope
Room air temperature (°C)	25	25	22	22
Room air humidity ratio (–)	0.010	0.010	0.005	0.005
Plenum air temperature (°C)	13	13	55	55
Plenum air humidity ratio (–)	0.009	0.009	0.005	0.005
Ambient air temperature (°C)	27	45	24	0
Ambient air velocity (m s^{-1})	0.1	0.1	0.1	0.1

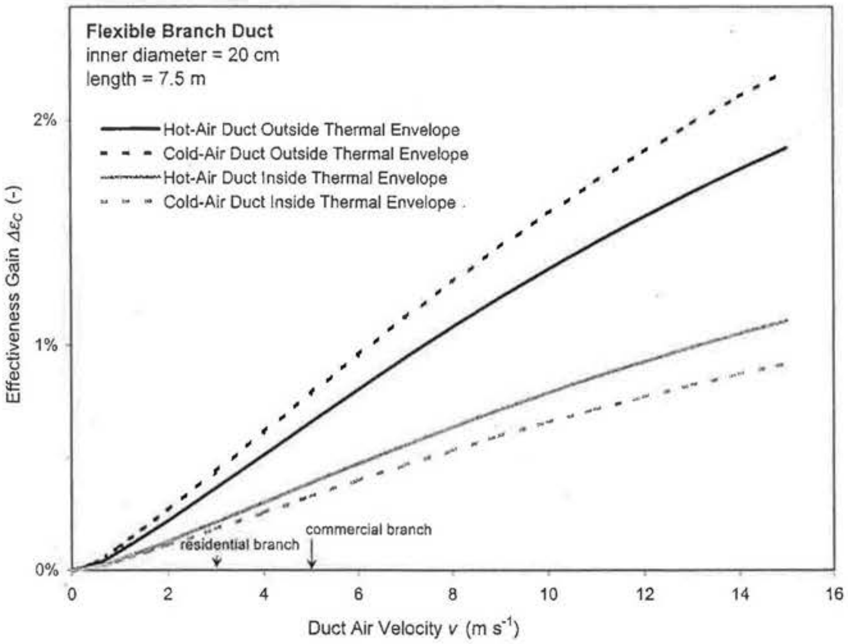

Fig. 5. Variation with duct air speed of the effectiveness gain achieved by encapsulating the air-facing surface of the fiberglass-insulated, flexible branch duct described in Table 3.

air — approximately $|T_A - T_\infty|$ — was greater for the former than for the latter. The effectiveness gains of hot-air ducts were higher than those of cold-air ducts for the same reason.

Eq. (7) also predicts that effectiveness gain increases with duct length and the sensitivity of insulation conductivity to air speed, and decreases with the duct's inner hydraulic diameter. The rigid duct was longer than the flexible duct, but the flexible duct had a smaller inner hydraulic diameter and had insulation whose conductivity was more sensitive to air speed. The rigid duct's lower emissivity also reduced the magnitude of its conductance

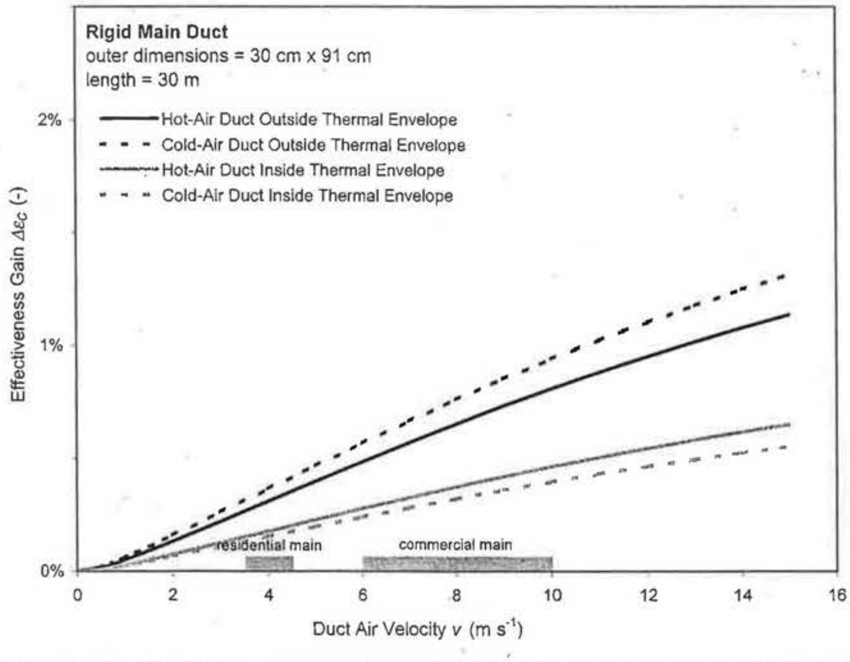

Fig. 6. Variation with duct air speed of the effectiveness gain achieved by encapsulating the air-stream surface of the fiberglass-insulated, rigid main duct described in Table 3.

Table 5
Effectiveness gains for flexible branch ducts and rigid main ducts at air speeds recommended for residential and commercial systems

Effectiveness gain (%)	Residential (%)	Commercial (%)
Flexible branch ducts	0.2–0.4	0.3–0.8
Rigid main ducts	0.15–0.45	0.2–0.9

change. The net result was that at a given air speed, the flexible duct's effectiveness gains were higher than those of the rigid duct.

5. Conclusions

The measured conductivity of a flexible duct's low-density internal fiberglass-blanket insulation increased with the square of the duct air speed, rising by 140% as the duct air speed increased from 0 to 15 m s^{-1}. At air speeds recommended for branch ducts, the conductivity of low-density flexible-duct insulation would increase by 6% above its still-air value in a residential system, and by 16% in a commercial system.

The conductivity of a rigid duct's high-density internal fiberglass insulation is theoretically predicted to increase with the square of the duct air speed at about half the rate of the low-density flexible duct insulation, rising by 66% as the duct air speed increases from 0 to 15 m s^{-1}. At air speeds recommended for main ducts, the conductivity of high-density rigid-duct insulation would increase by 4%–6% above its still-air value in a residential system, and by 11%–29% in a commercial system.

The measured total conductance of the pervious-core, insulated flexible duct increased linearly with duct air speed at a rate similar to that reported by an earlier study, but the variation was observed to begin at zero air speed, rather than at 5 m s^{-1} as previously reported.

Simulations indicate that encapsulating the air-stream surface of internal fiberglass duct insulation with an impervious barrier can increase the effectiveness with which a duct delivers the thermal capacity of supply air by 0.15%–0.9% in typical duct systems. Effectiveness gains in commercial systems were approximately twice those in residential systems because commercial systems operate at higher duct air speeds. Gains decrease with duct diameter, and increase with duct air speed, duct length, magnitude of the difference in temperature between the supply air and the duct's surroundings, and the sensitivity of the insulation's conductivity to duct air speed.

English symbols

A	cross-sectional area of duct (m^2)
c_p	specific heat of air/unit mass (J kg^{-1} K^{-1})
C	thermal capacity of supply air (W)
d_h	hydraulic diameter of duct (m)
H	enthalpy/unit mass dry air (J kg^{-1})
k	effective thermal conductivity (W m^{-1} K^{-1})
l	duct length (m)
$\dot{m}_a$	mass flow rate of the dry-air component of supply air (kg m^{-3})
P	duct perimeter (m)
r	duct radius (m)
$\mathfrak{R}$	characteristic thermal resistance of duct energy balance (m^2 K W^{-1})
R	thermal resistance (m^2 K W^{-1})
T	air temperature (K)
$\bar{T}$	volumetric mean air temperature (K)
U	thermal conductance (W m^{-2} K^{-1})
v	bulk velocity of axial duct airflow (m s^{-1})

Greek symbols

γ_T	temperature sensitivity of insulation's effective thermal conductivity (K^{-1})
γ_v	velocity sensitivity of insulation's effective thermal conductivity (s^2 m^{-2})
$\Delta\varepsilon_C$	effectiveness gain (−)
ε_C	thermal capacity delivery effectiveness (−)
ρ	density (kg m^{-3})

Subscripts

a	air
A	duct inlet
B	duct outlet
f	fiberglass
f0	fiberglass with still internal air
i	inner wall or inner air film
o	outer wall or outer air film
R	conditioned room
∞	duct surroundings

Superscripts

*	evaluated at reference temperature of 24°C

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