TESTING AND MODELLING OF FLEXIBLE AIR DUCT HEAT LOSSES

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Too often houses with ducted systems are not cooled sufficiently in summer or heated adequately in winter because of poor equipment selection or design. One cause is underestimation of the heat gain (or loss) from flexible duct under floors or in roof spaces. The authors' research tests have found that insulated flexible air ducts may have thermal performance considerably less than expected from guarded hot plate tests of flat insulation samples because of insulation compression, lack of insulation seam overlap, or air percolation through the insulation.

Using test and modelling procedures in this paper, one can now better estimate these losses and rate insulation of heating or cooling flexible air ducts more accurately. These procedures are based upon extensive flexible duct testing, modelling, and research at Enersonics Pty Ltd and James M Fricker Pty Ltd over several years.

Part 1. A new Standard Test Method to determine the Thermal Performance of Insulated Flexible Air Duct

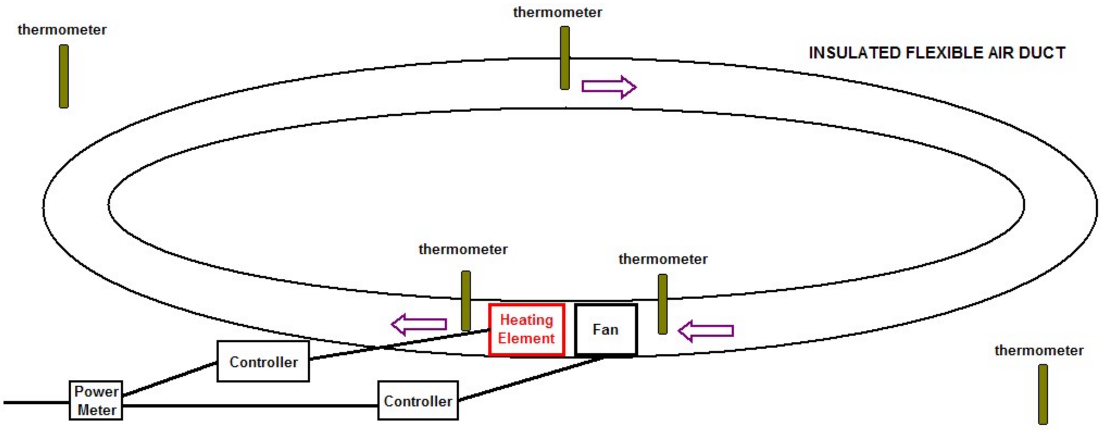
This economic and simple test method researched by the author attempted to simulate applications where heated air blows through a flexible air duct resting on ceiling rafters.

TEST SETUP

Connect four x 3m lengths (or one 12m length) of 200 mm or 300 mm diameter sample insulated flexible air duct into a horizontal circular loop (i.e., a toroid or donut), and support on wooden blocks roughly 0.6 metres apart (simulating duct laying on ceiling rafters). Within the duct loop, have installed an axial fan and electrical resistive heating element. The axial fan has the same diameter as the inside diameter of the flexible air duct. Use standard metal connectors and PVC duct tape, and tape both the inner and outer sleeves per normal installation practice. Fit substantial insulation around the casing of the axial fan so its outward heat loss does not affect test results.

Connect the resistive heater to a variable transformer, and monitor the total electrical input power (fan plus heater).

Fit a calibrated hot wire anemometer through holes in the inner and outer duct sleeves, and seal both penetrations with sealant or duct tape.



TEST METHOD

Start the axial fan and adjust the total power input to approximately 300 Watts and wait for two hours for temperatures to stabilise, while adjusting the power to obtain a steady state internal air temperature of 40 to 50°C.

Once steady state conditions are achieved, do not adjust the transformer and log the total electrical power input, in-duct air speed, and in-duct and room air temperatures.

Using the results of steady state conditions, do calculations according to the following example:

Calculation of duct Heat Loss Coefficient

Parameter		Qty	Formula
Nominal and inner duct diameter (mm):	D	200	
Insulation thickness (mm):	y	20	
Nominal duct length (m):		12	
Installed duct centre-line length (m):	L	10.9	
Insulation area based on mean dia.(m^2):	A	7.53	$A = L \cdot \pi \cdot (D + y) / 1000$
Air velocity (m/s):	V	5.0	(should be more than 3)
Air flow rate (L/s):	Q	157	$Q = V \cdot \pi \cdot (D / 1000)^2 / 4 \cdot 1000$
In-duct mean air temperature (°C):	t_i	42.0	
Room ambient air temperature (°C):	t_o	20.0	
Steady state temp. difference (K):	Δt	22.0	$\Delta t = t_i - t_o$
Steady state total heat input (W):	W	360	
Heat Loss Coefficient (W/linear m.K):	**HLC**	**1.50**	$HLC = W / L / \Delta t$
=> Thermal conductivity (W/m.K):	k	0.043	$k = W / A / \Delta t \cdot y / 1000$
Resistivity (m.K/W):	r	23	$r = 1 / k$
Temperature drop over duct length (K):	t_d	1.9	$t_d = W / 1.2 / Q$

USE: Heat Loss (Watts) = HLC • Duct length • Air-to-air temperature difference

This method derives a Heat Loss Coefficient (HLC) for easy thermal calculations. HLC is based upon the duct length as this is simpler (and more accurate) to use than an overall thermal conductivity (k) and insulation thickness. HLC is independent of installed insulation thickness which cannot be measured with accuracy.

The Heat Loss Coefficient is here defined as the heat lost (Watts) per installed duct length (metres) per temperature difference (Kelvin) between the air inside and outside of the duct.

As duct is flexible and tends to relax to approximately 5% less than its nominal stretched length, HLC uses installed length.

Example of use of Heat Loss Coefficient

For 5°C roof space air temperature, 50°C ducted air temperature, how much heat is lost from 10 m of the example glasswool insulated duct?

Ans: Heat loss (Watts) = $HLC \times L \times \Delta t = 1.50 \times 10 \times (50-5) = 675$ Watts!

For ducts of other sizes, the heat loss is approximately given by multiplying the above heat loss by the ratio of duct nominal diameters. E.g. for 400 mm duct, the loss would be 2 x 675 = 1,350 Watts.

UNCERTAINTY OF MEASUREMENT

The principal source of error in the test method is the thermometer uncertainty, hence having a large temperature difference between ambient air and in-duct air maximises accuracy. For the thermometers used and a 20K temperature difference, the estimated uncertainty of resistance and HLC measurements is 2%.

Q. Can one simply use insulation conductivity or thermal resistance determined from flat hot plate tests?

Measurement of the glasswool insulation removed from a few popular Australian insulated flexible air ducts revealed similar insulation properties:

	Nominal	Actual
Thickness:	25	20 mm
Density:	12	15 kg/m³

"Actual" refers to the insulation of fully extended duct which is still slightly compressed between the outer and inner duct sleeves. From the AIRAH Handbook, the insulation thermal conductivity can be deduced from this as approximately k_i=0.040 W/m•K.

Use of the AIRAH Handbook data is appropriate for heat transfer through a flat sheet, however, with flexible insulated air duct, there are:

- Convective heat transfer from the moving air to the inner duct surface (dependent upon air velocity),
- Conductive heat transfer through the insulation and sleeve materials, and
- Convective and radiative heat transfer from the outer sleeve to ambient conditions.

Using the nominal insulation thickness, the duct-tested overall thermal conductivity for the above example was determined as 0.043 W/m•K, which is 8% higher than the AIRAH Handbook conductivity value alone. This confirms that the use of the value for a flat sheet (even at the higher density) is not accurate for use in flexible ducts, possibly because the compression is not uniform. Comparison tests have confirmed that air leaking through the inner sleeve acoustic treatment perforations and moving through the glasswool in the direction of the pressure gradient, also reduces insulation performance.

Other tests have indicated that using the raw published insulation thermal conductivity for determining flexible duct heat loss usually gives inaccurate results.

Part 2. A Heat Transfer Model for Flexible Air Duct Performance

A computer model was developed by Dr Peter Johnson to predict the thermal behaviour of insulated flexible air ducts at flow rates and temperature conditions different to tested conditions. The theoretical model is based on the use of standard steady conduction, radiation and convection theory, modified by Reynolds Analogy. This model has been used to successfully predict the performance of sample ducts for different conditions.

Firstly, the fairly arbitrary test condition was modelled by the software, with iterative adjustment of the insulation rating until the predicted heat loss matched the test result, for the same conditions. Refer cases A and A1 below.

A. INSULATED SAMPLE "A" -TEST RESULT

Duct inner diameter = 300 mm
Duct axis length = 11 m
Insulation thickness = 24 mm
emittance of duct exterior = 0.87
Mean air velocity = 7.6 m/s
Air flow rate = 537 L/s
Duct friction factor = 0.07
Inner duct mean air temperature = 42.5 °C
Ambient air temp. outside duct = 19.9 °C
Air heat delivered => 15 kW
Total heat loss expected => 533 W, = 3.6%
Heat Loss Coefficient, HLC => 2.145 W/m•K
Total thermal resistance "R_T" => 0.475 m^2•K/W

A1. INSULATED SAMPLE "A" - MODEL MATCH OF TEST RESULT

Duct inner diameter = 300 mm
Duct axis length = 11 m
Insulation thickness = 24 mm
Insulation thermal conductivity = 0.0695 W/m•K
Insulation thermal resistance "R" = **0.3453** m^2•K/W
Insulation thermal resistance including surface film = 0.4653 m^2•K/W
Emittance of duct exterior = 0.87
Mean air velocity = 7.6 m/s
Air flow rate = 537 L/s
Duct friction factor = 0.07
Inner duct mean air temperature = 42.5 °C
Inner duct surface temperature => 42 °C
Outer duct surface temperature => 25.6 °C
Ambient air temp. outside duct = 19.9 °C
Air heat delivered => 15 kW
Total heat loss expected => 533 W, = 3.6%
Heat Loss Coefficient, HLC => 2.145 W/m•K
Total thermal resistance "R_T" => 0.475 m^2•K/W

NOTE: "R" was determined by its iterative adjustment to obtain tested heat loss.

Once the insulation rating (“R”) was established, the influence of other factors, e.g. emittance of outer sleeve and insulation thickness, were investigated.

Refer cases A2 and A3 below.

A2. INSULATED SAMPLE "A" - MODEL FOR REFLECTIVE DUCT

Duct inner diameter = 300 mm
Duct axis length = 11 m
Insulation thickness = 24 mm
Insulation thermal conductivity = 0.0695 W/m•K
Insulation thermal resistance "R" = 0.3453 m^2•K/W
Insulation thermal resistance including surface film = 0.6133 m^2•K/W
Emittance of duct exterior = 0.05
Mean air velocity = 7.6 m/s
Air flow rate = 537 L/s
Duct friction factor = 0.07
Inner duct mean air temperature = 42.5 °C
Inner duct surface temperature => 42.1 °C
Outer duct surface temperature => 29.6 °C
Ambient air temp. outside duct = 19.9 °C
Air heat delivered => 15 kW
Total heat loss expected => 407 W, = 2.7%
Heat Loss Coefficient, HLC => 1.636 W/m•K
Total thermal resistance "R_T" => 0.622 m^2•K/W

NOTE: "R" is from model case A1. In this run, the emittance was changed to 0.05.
Thus a reflective outer sleeve enhances performance of 25mm (1") insulation by 31%.

A3. "A" MODEL, DOUBLED INSULATION THICKNESS & REFLECTIVE

Duct inner diameter = 300 mm
Duct axis length = 11 m
Insulation thickness = 48 mm
Insulation thermal conductivity = 0.0695 W/m•K
Insulation thermal resistance "R" = 0.6906 m^2•K/W
Insulation thermal resistance including surface film = 0.9729 m^2•K/W
Emittance of duct exterior = 0.05
Mean air velocity = 7.6 m/s
Air flow rate = 537 L/s
Duct friction factor = 0.07
Inner duct mean air temperature = 42.5 °C
Inner duct surface temperature => 42.3 °C
Outer duct surface temperature => 26.4 °C
Ambient air temp. outside duct = 19.9 °C
Air heat delivered => 15 kW
Total heat loss expected => 275 W, = 1.8%
Heat Loss Coefficient, HLC => 1.105 W/m•K
Total thermal resistance "R_T" => 0.989 m^2•K/W

NOTE: This is case A2 with insulation thickness doubled.
A reflective outer sleeve with 50mm (2") insulation achieves ~ R1.0 m^2•K/W

MODEL RESULTS, HEATING MODE

Although tests were often not at standard application conditions, the computer model allowed prediction of performance at those conditions. For a typical Australian winter heating application, the model predicted performance where the air temperature in the duct was 50°C, the ambient temperature 5°C, and the in-duct velocity 4 m/s. The resulting Heat Loss Coefficient was computed as 2.11 W/linear m•K.

MODEL RESULTS, COOLING MODE

Similarly, a flow situation was modelled where the air temperature in the duct was 15°C, the ambient temperature was 50°C and the in-duct velocity was 4 m/s. The resulting heat loss coefficient was computed as 2.20 W/linear m•K.

For this example acoustic duct which had a slightly perforated inner sleeve, the computed thermal conductivity for cooling mode was 5% more than for heating mode.

A4. INSULATED SAMPLE "A" - TYPICAL HEATING APPLICATION

Duct inner diameter	=	300	mm
Duct axis length	=	12	m
Insulation thickness	=	24	mm
Insulation thermal conductivity	=	0.0695	W/m•K
Insulation thermal resistance "R"	=	0.3453	m^2•K/W
Insulation thermal resistance including surface film	=	0.4633	m^2•K/W
Emittance of duct exterior	=	0.87	
Mean air velocity	=	4.0	m/s
Air flow rate	=	283	L/s
Duct friction factor	=	0.07	
Inner duct mean air temperature	=	50.0	°C
Inner duct surface temperature	=>	48.2	°C
Outer duct surface temperature	=>	16.0	°C
Ambient air temp. outside duct	=	5.0	°C
Air heat delivered	=>	15	kW
Total heat loss expected	=>	1139	W, = 7.6%
Heat Loss Coefficient, HLC	=>	2.109	W/m•K
Total thermal resistance "R_T"	=>	0.483	m^2•K/W

A5. INSULATED SAMPLE "A" - TYPICAL COOLING APPLICATION

Duct inner diameter	=	300	mm
Duct axis length	=	12	m
Insulation thickness	=	24	mm
Insulation thermal conductivity	=	0.0695	W/m•K
Insulation thermal resistance "R"	=	0.3453	m^2•K/W
Insulation thermal resistance including surface film	=	0.4458	m^2•K/W
Emittance of duct exterior	=	0.87	
Mean air velocity	=	4.0	m/s
Air flow rate	=	283	L/s
Duct friction factor	=	0.07	
Inner duct mean air temperature	=	15.0	°C
Inner duct surface temperature	=>	16.3	°C
Outer duct surface temperature	=>	42.4	°C
Ambient air temp. outside duct	=	50.0	°C
Air heat delivered	=>	-12	kW
Total heat loss expected	=>	-923	W, = 7.7%
Heat Loss Coefficient, HLC	=>	2.197	W/m•K
Total thermal resistance "R_T"	=>	0.463	m^2•K/W

VELOCITY EFFECT

With only 1.0 m/s in-duct air velocity, internal convective heat transfer is reduced and the heat loss is approximately 11% less than for 4 m/s. (However, in applications with lower air flow rates, useful heat transfer to room registers is reduced.)

FRICTION FACTOR

When the duct inner surface is very smooth, there is less in-duct convective heat transfer. A typical flexible duct friction factor of 0.064 was used in the preceding model results. If the duct surface was smooth (zero friction factor), heat loss was determined to be typically 6% less. Conversely, if the flexible duct was poorly installed with excessive bends, heat loss per metre could be increased by 4%.

FIRE-RATED DUCT

The preceding base result was for a typical duct with polythene outer sleeve and perforated foil inner sleeve. For fire-rated duct, the outer sleeve is also a foil laminate. (This reduces susceptibility to fire radiant heat.) The outer sleeve thus has lower emittance, and hence lower radiative heat transfer. Model trials indicate heat loss is typically reduced by 11% for flexible duct having a reflective foil outer sleeve.

CONCLUSIONS

A test method has been developed and proven to be suitable for determining the total heat loss from insulated flexible air duct.

A computer model of the thermal behaviour of insulated flexible air duct has proven to be useful in predicting performance for conditions different to those in the test, for example, for standard temperatures for heating and cooling applications.

Once the standard HLC is determined, the heat loss/gain from an insulated flexible air duct may be estimated by:

Heat Loss (Watts) = HLC x Duct length x Air-to-air temperature difference

The main factors in reducing heat loss from insulated flexible air duct are:

- improving the insulation,
- optimised duct sizing,
- using unperforated inner lining,
- using a reflective outer sleeve, and
- minimising the length of ducting.

If insulation wrap overlap or compression varies with duct diameter, the Heat Loss Coefficient (HLC) should be tested for the different diameter by the above described test method.

BIBLIOGRAPHY

Standards Australia, AS 4254-2002 *Ductwork for air-handling systems in buildings*

Australian Institute of Refrigeration Air conditioning and Heating (AIRAH) Handbook, 4th Edition (2007).

About the authors

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POSTSCRIPT: Note that for a reflective surface to be effective at reducing radiation heat loss, the surface must have a low infrared emittance. (Some products are visibly reflective, but have high infrared emittance because of a transparent clear plastic coating. They perform little different to a non-reflective surface.)

For further information, see http://fricker.net.au