Study into the operation of a convector heater at low temperatures

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The study described below was executed on behalf of the Novem and aims to discover and illustrate whether and how convectors can be incorporated into a low-temperature heating system in new and existing dwellings, possibly with additional insulating measures. This study is required because the market is uncertain as to whether convectors actually work at low temperatures. The total heat emission and cold downdraught compensation at a specific over-temperature are two important aspects of the operation. The convector heating units used are traditional wall and underfloor convector heaters.

The first aspect relates to the heat emission of a convector heater as a function of the over-temperature. This is (theoretically) described by a power law. The measurements confirm the dependency from an over-temperature of 5^{o}C, which coincides with the bottom limit at which the heat emission can still be measured sufficiently accurately.

The second aspect relates to cold downdraught. Cold downdraught is a phenomenon determined by many factors, such as the geometry and temperature of the space, convector heater and cold surfaces, respectively. This makes general statements about cold downdraught compensation difficult to apply to specific situationst. Simulation can offer a solution if it is able to predict the cold downdraught with sufficient accuracy. The simulations of the cold downdraught for the specific set-ups with the wall and underfloor convector heaters were executed with MatLab/FemLab. The simulated over-temperatures required for cold downdraught compensation coincide with the above-mentioned values, with a margin of 2.5^{o}C. The software with the associated model is therefore suitable as a tool to predict cold downdraught compensation for the geometries and preconditions described in this report.

INTRODUCTION

The increasing levels of insulation in dwellings means that the heating capacity and heating energy requirements in each home are decreasing. When heat emission systems are used, this means that in principle the supply temperature can be reduced. The consequence is a low return temperature. This can have a favourable impact on the output of the main heating element (e.g. a boiler or heat pump). In general, the lower the mean temperature to the heating element, the higher the efficiency. As such, primary energy can be saved by minimising the temperature of the heat emission system. The study was executed on behalf of the Novem and aims to discover and illustrate whether and how convectors can be incorporated into a low-temperature heating system in new and existing dwellings, possibly with additional insulating measures. This study is required because the market is uncertain as to whether convectors actually work at low temperatures. The operation of a convector heater is based on the principle that hot air rises, generating air circulation. The movement of air transfers the heat from the convector heater's surface to the environment. When there is a big temperature difference between the convector heater's surface and the surrounding air, there is a considerable driving force that maintains the movement of air. In case of a low temperature difference between the convector heater's surface and the surrounding air, there is barely any driving force so that barely any circulation – and therefore heat transfer – is generated. This pose the question “what is the lowest surface temperature of a convector heater at which it can emit sufficient heat for heating purposes?” Aspects that are important in this context are: a) The total heat emission of the convector heater, and b) cold downdraught compensation. To determine this, we have executed simulations and measurements with a traditional convector-type JAGA placed under a cold surface. The results of measurements taken in a laboratory and of simulations were compared (validation of the simulation model). With the aid of the validated simulation models, other situations (convector heater size and geometry of the cold surface and space) can be calculated and evaluated. The study therefore provides insight as to whether and how convectors can be incorporated into a low-temperature heating system. The objective of this project is to discover through scientific study the minimum temperature difference between a traditional convector heater and the air at which the convector heater can still operate effectively for heating purposes. The total heat emission and cold downdraught compensation of a traditional convector heater were studied as a function of the temperature difference between the average surface temperature of the convector heater and the air. The operation at low temperatures of two types of convector heaters, a wall and an underfloor convector heater, was assessed on the basis of simulations and measurements in a climate room. The results lead to statements with regard to the minimum surface temperatures of these convector heaters that are required for heating purposes by: a) verifying the validity of the power law (cf. formula (1)) by measuring the total heat emission at low temperatures and b) measurements and CFD simulation of the cold downdraught compensation in a climate room.

THEORY

Dimensioning a convector heater in the design phase

There are at least two important aspects to dimensioning a convector heater in the design phase. In the first place, the heat emission of the convector heater(s) contributes to the total heat capacity. Assuming that only convector heaters will be used to heat the space in question, the heat capacity will be generated entirely by the convector heaters. The second aspect is the compensation of possible cold downdraught. This means that the convector heaters will be placed in the immediate vicinity of surfaces that are likely to be cold, such as windows and outer walls. The width of the convector heater generally coincides with the width of the cold surface. A wall convector heater is usually used for a window; an underfloor convector heater for an outer wall. The surface temperature of the cold surface provides the measure for compensating cold downdraught.

Clearly the surface temperature of glass depends heavily of the type of glass. E.g. for an outside temperature of –5^{o}C, an indoor temperature of 22^{o}C and heat transfer coefficients from the inside of 7.7 W/m^{2}K, the glass surface temperatures are:

Glazing type	**U value [W/m^{2}K]**	**Surface temperature [^{o}C]**
double glazing	3.0	11.5
hr glazing	1.8	15.7
hr ++ glazing	1.0	18.5

Table I Surface temperatures for different types of glazing.

The minimum required surface temperature of the convector heater to compensate cold downdraught will reduce as the U value of the glazing falls.

The designer is free to choose to the type of convector heater (differently sized heat exchangers) and the supply temperature of the water. By selecting the lowest possible supply temperature, the efficiency of the heat pump will generally increase. The aim is therefore the lowest possible supply temperature.

The heat emission of a convector heater

In the design, it is assumed that the effective output of a convector heater can be expressed with the aid of the following power law [1]-[5]:

$$Q = C \cdot \Delta T^n, \quad with: \qquad \Delta T = \frac{Tv + Tr}{2} - Tl \tag{1}$$

Q: Effective output [Watt]
C,n: Constants
ΔT: Over-temperature [^{o}C]
Tv: Supply temperature [^{o}C]
Tr: Return temperature [^{o}C]
Tl: Ambient temperature (air) [^{o}C]

When convector heaters are used, a supply temperature of over 70^{o}C is generally assumed. Using low-temperature heating and convector heaters reduces the supply temperature (to 30^{o}C). The design output can be expressed as a function of the total length of the convector heater and the average temperature difference between the convector heater surface and air temperature.

When written as a formula, this results in:

$$Q_{design} = K \cdot L \cdot \Delta T^n \tag{2}$$

L: Convector length (= 1.8) [m]

K,n: Constants (K=5.6, n=1.37)

where K and n were determined with the aid of manufacturer's data [10] in this case.

Cold downdraught compensation when using a convector heater

Cold downdraught is a downward (cold) flow that is generated when the air near a cold surface (e.g. single glazing) cools down, locally increasing the density of the air compared to the average air density in the space. These differences in air density are the driving force behind the flow that, if sufficiently strong, is often perceived as a draught. To simulate the cold downdraught we used a finite-element package FemLab [7], which is able to simulate models of 2D flow resulting from convection. To this end, the Navier-Stokes equations were modelled with the Boussinesq approach. The model was validated with measured flows [8]. The flow problem is really a 3D problem. However, due to the combination of a small length scale (the distance between the convector fins (5.5 mm) and a large length scale (the dimensions of the room (5 m)) it has proven impossible (as yet) to simulate this directly with the software described above. The 3D geometry can be approached with a 2D geometry in combination with a correction for the over-temperature used. The 3D flow of the convector can be approached in 2D with the following correction for over-temperature (cf. Annex):

$$\Delta T_{2D} \approx 4 \cdot \Delta T_{3D} \tag{3}$$

Where ΔT_{3D} = Actual over-temperature based on 3D geometry
ΔT_{2D} = Associated over-temperature based on 2D geometry

MEASUREMENTS

Two wall convector heating units (manufacturer Jaga, type Canal – Plus Twin) were placed in parallel before the cold wall in a climate room. The dimensions of the climate room are: length x width x height = 9.7 x 5.2 x 2.7 m. The external dimensions of the wall convector heaters are: length x width x height = 1800 x 130 x 300 m. The surface temperature of the cold wall of the climate room is the same as the surface temperature of glass inside a residence. The wall temperature of the cold surface can be adjusted with the aid of a computer. The return temperature of the water is also specified. The water is heated with the aid of an electric boiler. The space contains four measuring columns with sensors to measure the air temperature with the aid of thermocouples and the air speed with the aid of hot-wire anemometers (dantecs). The water flow is measured with a flow meter (Brooks). The measurement data is stored with loggers.

Virtually the same measurement set-up was used for the measurements with the underfloor convector heater as for the wall convector heater. To be able to install an underfloor convector heating unit in the climate room, the floor was raised by 0.5 metres. The measurements of the climate room in this case are: length x width x height = 9.70 x 5.2 x 2.2 m. The measurement set-ups are shown in figure 1:

Figure 1 The measurement set-ups with wall convectors (left) and underfloor convectors (right)

Every measurement has a number of intervals (different over-temperatures). In an interval, a stable situation is reached. These are clearly shown in the graphs. The figures below show several measured values as a function of time:

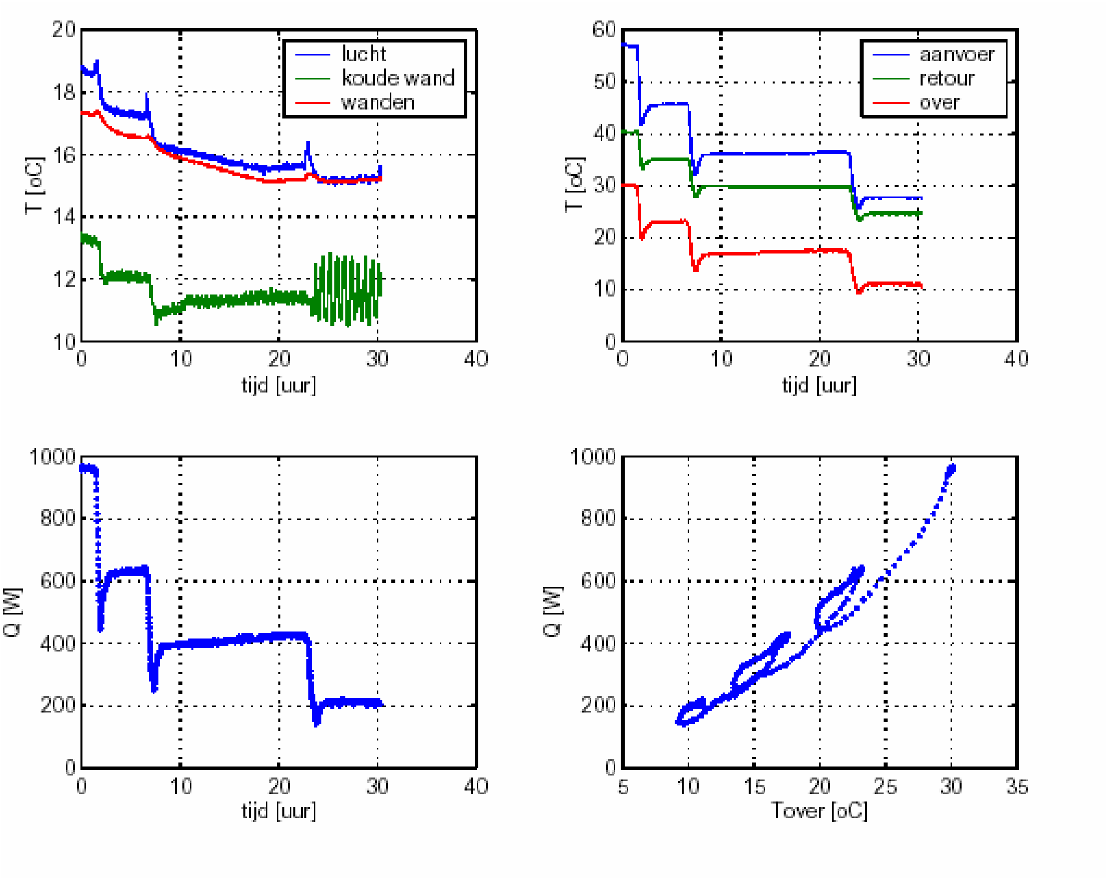
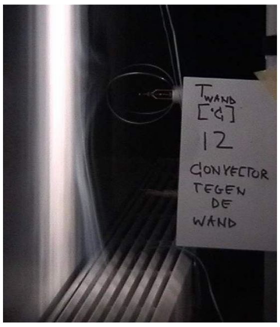
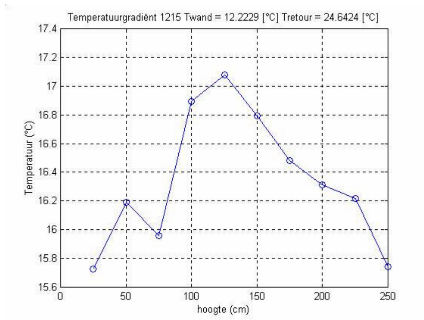


Figure 2 Measured time series of air and wall temperatures (left top), supply and return temperatures and over-temperature (right top), the actual efficiency (left bottom), and the derived power law (right bottom).

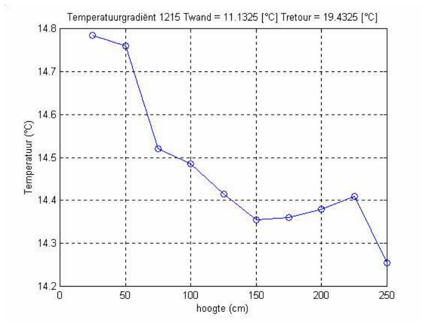
We also measured air speeds as a function of time in various locations. During some experiments we made infrared recordings to gain insight into the surface temperature distribution of the convector heating unit.

During the experiments, smoke tests were conducted to visualise the air flow around the convector heater [6]. With the aid of these tests and the temperature curve above the convector as a function of height, it can be determined whether the cold downdraught is compensated.





a)



b)

Figure 3 a): Example of cold downdraught compensation: the warmer air from the convector heater moves in the direction of the cold wall in combination with an increase of air temperature from the top of the convector heater. b): Example of the absence of cold downdraught compensation: the warmer air from the convector heater does not move in the direction of the cold wall in combination with a drop in air temperature from the top of the convector heater.

This smoke test in figure 3a shows that the air flow from the convector heater is directed towards the cold wall. In combination with an increase of air temperature from the top of the convector heater. This shows that that the cold downdraught is indeed compensated.
The smoke test in figure 3b clearly shows that the air flow from the convector is not directed towards the cold wall in combination with a drop in air temperature from the top of the convector heater. This shows that the cold downdraught is *not* compensated.

Two situations were measured for the wall and underfloor convector set-up: one in which the convector heater is placed against the wall, and the other in which the convector heater is placed 10 cm from the (cold) wall.

MEASUREMENT RESULTS

Figure 4 shows the effective outputs of the wall convector heater as a function of the over-temperature for all variants.

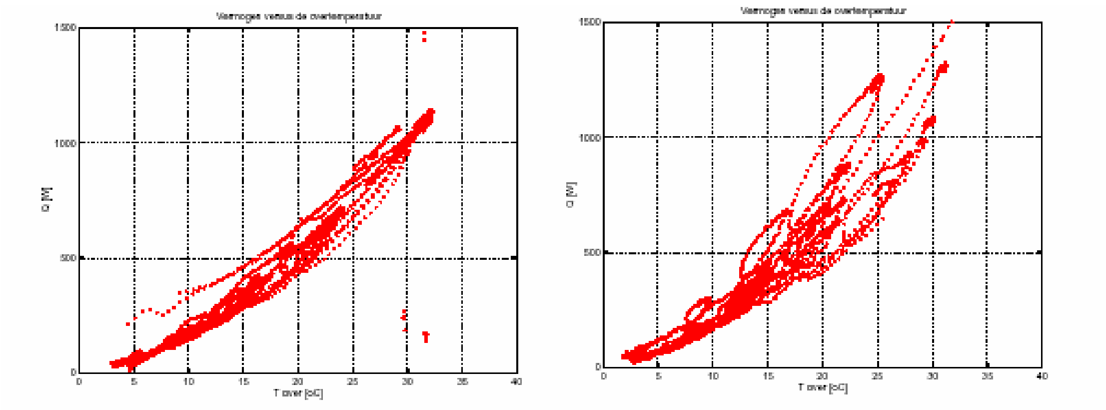


Figure 4 The effective outputs of the wall convector heater (left) and the underfloor convector heater (right) as a function of the over-temperature.

The figure above demonstrates that the power law is valid from an over-temperature of 5^{o}C.

The following table shows whether the cold downdraught is (yes) or is not (no) compensated by the convector heater in the situation of the described measurement set-up:

WALL CONVECTOR HEATING UNIT										
Twall [^{o}C]	Location: against the wall Tover [^{o}C]					Location: 10 cm from the wall Tover [^{o}C]				
	30	20	15	10	5	30	20	15	10	5
12	yes	yes	yes	yes	no	yes	yes	yes	yes	no
16	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
18	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
UNDERFLOOR CONVECTOR										
Twall [^{o}C]	Location: in the middle of the well Tover [^{o}C]					Location: against the wall Tover [^{o}C]				
	30	20	15	10	5	30	20	15	10	5
12	yes	yes	yes	yes	no	yes	yes	yes	yes	no
16	yes	yes	yes	yes	no	yes	yes	yes	yes	no
18	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

Table II. Presence of absence of cold downdraught compensation with the wall and underfloor convector heater for the different variants.

Glass type	**Surface temperature [^{o}C]**	**Measured required over-temperature [^{o}C] for wall convector heater**	**Measured required over-temperature [^{o}C] for underfloor convector heater**
double glass	11.5	10	10
hr glass	15.7	5	8
hr ++ glass	18.5	<5	<8

Table III. Presence of absence of cold downdraught compensation with the wall and underfloor convector heater for the different variants.

SIMULATION RESULTS

Wall convector heating unit

CFD (FemLab) was used to simulate the air flow of a cold wall (12^{o}C) and wall convector heater. The surface temperature (Topp=T_{2D}) of the convector heater and associated equivalent over-temperature (Tover_equivalent (= ΔT_{3D})) were increased step-wise. These results are shown in the figures below:

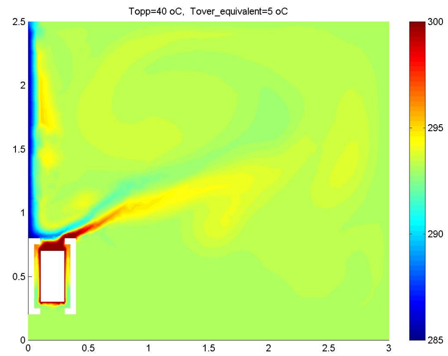


Figure 5. Simulation of the cold downdraught simulation (temperature distribution in [K]) at an equivalent over-temperature of 0^{o}C (top left), 2.5^{o}C (top right), 5^{o}C (bottom left) and 7.5^{o}C (bottom right)

The simulation shows that the cold downdraught is compensated at an equivalent over-temperature of 7.5^{o}C. This coincides with the results of measuring series variant: Twall=12^{o}C, convector heater location: against the wall, from table II. It was measured here that, at an over-temperature of 5^{o}C, no cold downdraught compensation occurs, but that it does from 10^{o}C.

Underfloor convector heating unit

CFD (FemLab) was used to simulate the air flow of a cold wall (12^{o}C) and an underfloor convector heater. The surface temperature (Topp=T_{2D}) of the convector heater and associated equivalent over-temperature (Tover_equivalent (= ΔT_{3D})) were increased step-wise. These results are shown in the figures below:

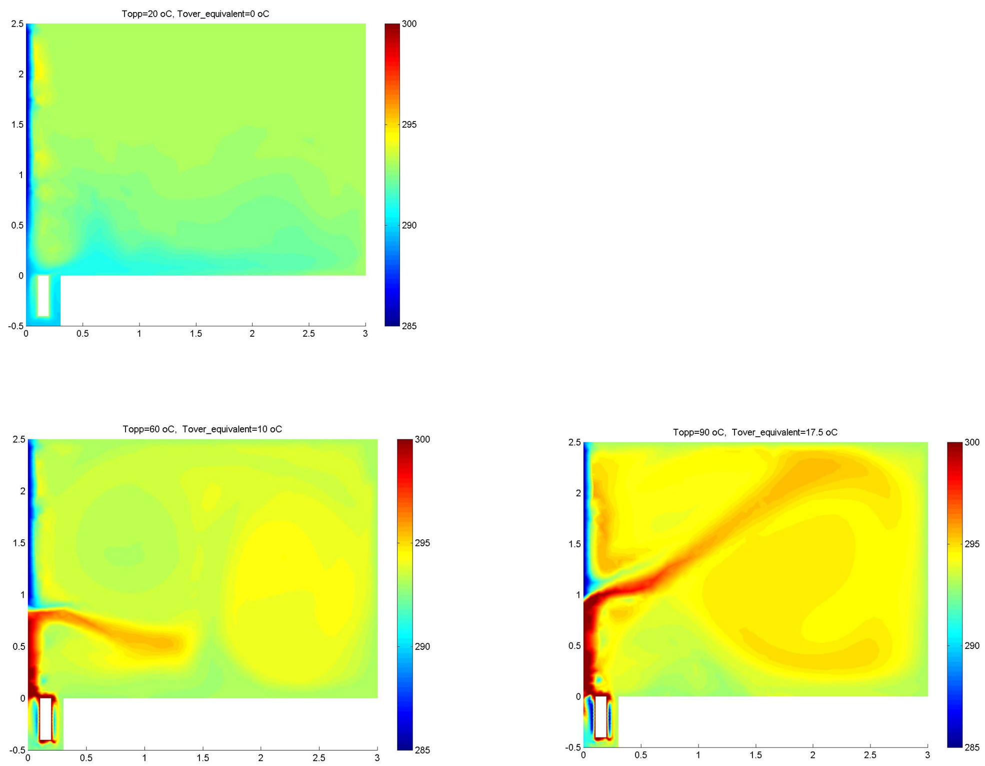


Figure 6. Simulation of the cold downdraught simulation (temperature distribution in [K]) at an equivalent over-temperature of 0^{o}C (top left), 5^{o}C (top right), 10^{o}C (bottom left), and 17.5^{o}C (bottom right)

The simulation shows that the cold downdraught is compensated at an equivalent over-temperature of 10^{o}C. This coincides with the results of measuring series variant: Twall=12^{o}C, convector heater location: against the wall, from table II. It was measured here that, at an over-temperature of 5^{o}C, no cold downdraught compensation occurs, but that it does at 10^{o}C.

CONCLUSIONS

The study concerns convective air flow, which is known to depend heavily on the geometry (dimensions of the space and dimensions and position of the convector heating unit) and preconditions (cold wall temperature and convector temperature). The results specified in this report are always based on a specific geometry and preconditions and can therefore not be extrapolated to other situations without further elaboration.

Validity of the power law
The heat emission of a convector is described by a power law. Starting at an over-temperature of 5°C, the heat emission can be measured sufficiently accurately with the set-up that was used. In all of these cases, the power law was found to be valid.

Measured cold downdraught compensation.
For the specific set-up with the wall convector heater and the underfloor convector heater, the over-temperatures were measured at which cold downdraught is just about compensated.

Simulations
The above-mentioned situations with a cold-wall temperature of approx. 12oC were simulated with the aid of CFD software (MatLab/FemLab). The simulated required over-temperatures coincide with the above-mentioned values, with a margin of 2.5°C. The software with the associated model is suitable as a tool to predict cold downdraught compensation for the geometries and preconditions described in this report.

SOURCES

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[5] COMSOL, Inc. FemLab (version 2.0) Reference Manual
[6] Schijndel A.W.M, Modeling and solving Building Physics Problems with FemLab, Building and Environment 38 (2003) pp. 319-327
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[8] Konvektco Nederland b.v, JAGA, Den Bosch, 1998.

ANNEX

Equation (3) was established as follows: The actual effective output of the convector heater is:

$$Q_{3D} = 5.6 \cdot L \cdot \Delta T_{3D}{}^{1.37} \tag{4}$$

[9] can be used to derive a formula for the effective output for flow along fins:

$$Q_{2D} = \alpha \cdot A \cdot \Delta T_{2D} \approx 1.6 \cdot \Delta T_{2D}{}^{0.3} \cdot L \cdot (2b + 2h) \cdot \Delta T_{2D} = L \cdot \Delta T_{2D}{}^{1.3} \tag{5}$$

where b = width of the fin (=0.1m) and h = height of the fin (=0.1m) These outputs must be the same per running metre:

$$\frac{Q_{3D}}{L} = \frac{Q_{2D}}{L} \tag{6}$$

It follows from (4), (5) and (6) that:

$$\Delta T_{2D}{}^{1.3} = 5.6 \cdot \Delta T_{3D}{}^{1.37} \tag{7}$$

(3) follows from the above relationship.