Simultaneous Conduction and Radiation Energy Transfer

Radiant energy can transfer from a colder to a warmer radiator.

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Abstract
The rigorous model of simultaneous thermal and radiant energy transfer proves energy transfer by radiation can flow from a colder radiator to a warmer one, heating the warmer one further. It explains and quantifies how dissimilar walls in a room can have different steady-state temperatures. Only the general laws of thermal and radiant energy transfer and the First Law of Thermodynamics, conservation of energy, are employed.

Introduction
Many claim radiant energy can only transfer from a hot radiator to a colder one. Otherwise the Second Law of Thermodynamics would be violated. While this is true for thermal energy transfer by conduction or convection, it is not true for radiant energy transfer.

How does a cold radiator transfer energy to warmer surroundings? It depends on absorptivity, emissivity and intensity differences at each radiating surface and on the presence of simultaneous conduction. We will show why temperatures of dissimilar room walls at steady-state are not be equal.

Conservation of Energy
Consider an object radiator at temperature T in a room of air and radiating surroundings at temperature Ts.

The First Law of Thermodynamics, conservation of energy for the radiator says: Rate of energy out/in by conduction at T to/from surroundings at Ts = rate of energy in/out by radiation from/to surroundings minus/plus the rate of energy accumulation/depletion within the radiating body.

Rate Out = Rate In - Rate of Accumulation

$$Qo(t) = Qi(t) - m\ Cp\ dT(t)/dt$$

Q's are energy transfer rates, m is body mass and Cp is its heat capacity. This ordinary differential equation can be integrated for transient response T(t) for given Qi(t) and Qo(t) functions of T, Ts and time, t, even when Q's depend on T.

At steady state, T is constant, dT/dt = 0, out/in = in/out and

$$Qo = Qi \qquad (1)$$

Let Qc be rate by conduction and Qr rate by radiation. Qo is Qc if Qc > 0. Qi is Qr if Qr > 0.

Qc = Qr

According to the First Law each Q must have the same sign, in = out. By convention, if both are positive, thermal energy flows out, radiant energy flows in and radiator T > surroundings Ts. Radiant energy transfers from cold surroundings to warm radiator. If both are negative, thermal energy flows in, radiant energy flows out and radiator T < surroundings Ts. Radiant energy transfers from cold radiator to warm surroundings. Radiant energy flow balances thermal energy flow.

This is a common source of confusion. Like all flows, energy flow has a direction, mathematically it is a vector. One must use care to get signs and directions right.

Energy Transfer Rate Laws

The general law of thermal energy transfer from a body at T to its surroundings at Ts by conduction and convection is

$$Qc = k(T - Ts),\ w/m^2 - K/100 \qquad (2)$$

where k > 0 is the of thermal energy transfer coefficient. It depends on materials and mode of conduction/convection. Assume k = 100 w/m^2 - K/100. Define T and Ts = deg K/100.

If Qc > 0, flow is Qo from body out to the surroundings; if Qc < 0, flow is Qi in to body from the surroundings.

The general law of radiant energy transfer[1] from surroundings to a radiator, derived in Appendix is:

$$Qr = 5.67 * (\alpha\ \varepsilon s\ Ts^4 - \alpha s\ \varepsilon\ T^4), \qquad (3)$$

where α and ε are the absorptivity and emissivity of the radiator and αs and εs are the absorptivity and emissivity of the surroundings. Each of these properties depends on composition, temperature and pressure. (I will assume they are constant here without loss of generality.) Equation (3) was derived[1] from Stefan – Boltzmann Radiation Law.

If Qr > 0, flow is Qi in from surroundings to the radiator; if Qr < 0, flow is Qo out to surroundings. Some analysists may think if T > Ts, Qr > 0, but this is not true here because Qr > 0 is defined to be Qi.

When T > Ts, Qc and Qr > 0, radiant energy flows in from lower surroundings Ts to higher radiator T. The direction of radiant energy flow depends on intensity differences, not temperature differences.

When $T < Ts$, Qc and $Qr < 0$, radiant energy flows out from lower radiator T to higher surroundings Ts.

$Qc = Qr; k(T - Ts) = 5.67 * (\alpha\ \varepsilon s\ Ts^4 - \alpha s\ \varepsilon\ T^4)$, (4)

Rearranging,

$kT + 5.67\ \alpha s\ \varepsilon\ T^4 = kTs + 5.67\ \alpha\ \varepsilon s\ Ts^4$; LHS = RHS (5)

Given Ts, we can find T, or vice versa.

$T = Ts$, if and only if $\alpha\ \varepsilon s = \alpha s\ \varepsilon$, ($Qc = Qr = 0$), which is rarely the case for dissimilar radiators.

If $\alpha s\ \varepsilon > \alpha\ \varepsilon s$, $T < Ts$ by inspection. If $\alpha s\ \varepsilon < \alpha\ \varepsilon s$, $T > Ts$.

There will always be a solution T for any given $Ts > 0$.

When both are black bodies, $\alpha = \varepsilon s = \alpha s = \varepsilon = 1$.

$kT + 5.67\ T^4 = kTs + 5.67\ Ts^4$, $T = Ts$ by inspection.

If no other energy transfer is involved and Kirchhoff Law applies to both, $\alpha = \varepsilon$, $\alpha s = \varepsilon s$

$kT + 5.67\ \varepsilon s\ \varepsilon\ T^4 = kT_0 + 5.67\ \varepsilon s\ \varepsilon\ Ts^4$, $T = Ts$ by inspection.

Poor Radiator Example
Assume $\alpha s = 0.9$, **$\varepsilon s = 0.8$**, $\alpha = 0.6$, $\varepsilon = 0.5$. $\alpha s\ \varepsilon = 0.45 < \alpha\ \varepsilon s = 0.48$.
$100\ T + 5.67 * 0.9 * 0.5\ T^4 = 100\ Ts + 5.67 * 0.6 *$ **0.8** Ts^4
$100\ T + 5.67 * 0.45\ T^4 = 100\ Ts + 5.67 *$ **0.48** Ts^4

Let Ts = 20C. We find T = about 23.473C > Ts
RHS = 100 * 2.9315 + 5.67 * **0.48** * 2.9315^4 = 293.15 + 5.67 * **0.48** * 73.8515
= 293.15 + **200.9944** = 494.144369
LHS = 100 * 2.96623 + 5.67 * 0.45 * 2.96623^4 = 296.623 + 5.67 * 0.45 * 77.4139
= 296.623 + 197.5217 = 494.144356, checks

Qc = k(T - Ts) = 100 * (2.9662 - 2.9315) = 3.473 out
$Qr = 5.67 * (\alpha\ \varepsilon s\ Ts^4 - \alpha s\ \varepsilon\ T^4)$ = 5.67 (0.6***0.8** * 2.9315^4 - 0.9*0.5 * 2.9662^4)
= 5.67 * (**0.48** * 73.8515 - 0.45 * 77.4139) = 5.67 * (**35.4487** - 34.8362) = 5.67 * 0.6125 = 3.4729 in. Close to Qc, round-off.

Note radiator T = 23.47 > surroundings Ts = 20, but colder surroundings transfer radiant energy into warmer radiator, heating it because $\alpha\ \varepsilon s > \alpha s\ \varepsilon$, 0.6*0.8 > 0.9*0.5. Qr = Qc = 3.473.

If T = Ts = 20, Qc = 0 and
Qr = 5.67 * (α εs Ts^4 - αs ε T^4) = 5.67 (0.6***0.8** * 2.9315^4 - 0.9*0.5 * 2.9315^4) = 5.67 * 2.9315^4 * (0.48 – 0.45) = 5.67 * 73.8515 * 0.03 = 12.562.

This means radiant energy is coming in but no thermal energy is leaving. The radiator T = 20 will increase, thermal energy starts to go out and incoming radiant energy decreases until a T = 23.473 is reached. Qr in drops from 12.562 to 3.473 and Qc out increases from 0 to 3.473, constant.

At steady state, radiator is T = 23.473 and surroundings Ts = 20. Energy is transferring out by conduction because T > Ts. Energy is transferring in by radiation because intensity of colder surroundings > radiator surface.

Qr = 5.67 (0.6***0.8** * 2.9315^4 - 0.9*0.5 * 2.96623^4) = 5.67 (0.48 * 73.8515 - 0.45 * 77.4140^4) = 5.67 * (**35.4487** - 34.8362) = 5.67 * 0.6125 = 3.473.

Radiant energy transfers in from surroundings at 3.473 even though surroundings Ts = 20 are colder than radiator at T = 23.473.

Since radiation rate increases as power of 4 and conduction rate increases linearly, there will always be a solution where Qr drops and/or Qc increases until they meet, Qc = Qr not = 0. Ts remains 20C and radiator warms to 23.473 at steady-state.

Good Radiator Example
Exchange αs ε for α εs. Radiator has higher α and ε; it is a better radiator.
Assume αs = 0.6, εs = 0.5, α = 0.9, ε = 0.8. αs ε = 0.48 > α εs = 0.45.
100 T + 5.67 * 0.6 * 0.8 T^4 = 100 Ts + 5.67 * 0.9 * 0.5 Ts^4
100 T + 5.67 * 0.48 T^4 = 100 Ts + 5.67 * 0.45 Ts^4

Let Ts = 20C. We find T = about 16.6004C > Ts
RHS = 100 * 2.9315 + 5.67 * 0.45 * 2.9315^4 = 293.15 + 5.67 * 0.45 * 73.8515
= 293.15 + **188.4322** = 481.582221
LHS = 100 * 2.897504 + 5.67 * 0.48 * 2.897504^4 = 289.7504 + 5.67 * 0.48 * 70.4849
= 289.7504 + 191.8317 = 481.582143, checks

Qc = k(T - Ts) = 100 * (2.8975 - 2.9315) = - 3.3996 out = 3.400 in
Qr = 5.67 * (α εs Ts^4 - αs ε T^4) = 5.67 (0.9***0.5** * 2.9315^4 - 0.6*0.8 * 2.8975^4)
= 5.67 * (**0.45** * 73.8515 - 0.48 * 70.4849) = 5.67 * (**33.2331** - 33.832759) = 5.67 * (- 0.5995) = - 3.3995 in or 3.400 out. Close to Qc, round-off.

Note radiator T = 16.60 < surroundings Ts = 20, but colder radiator transfers radiant energy out to warmer surroundings, because αs ε > α εs, 0.6*0.8 > 0.9*0.5. Qr = Qc = - 3.400. Since it is a good radiator, it is cooler than the poorer one. Thermal energy comes in; radiant energy goes out.

Decrease εs case.
Surroundings have lower emissivity.
Assume αs = 0.9, **εs = 0.7**, α = 0.6, ε = 0.5. αs ε = 0.45 > α εs = 0.42.
100 T + 5.67 * 0.9 * 0.5 T^4 = 100 Ts + 5.67 * 0.6 * **0.7** Ts^4
100 T + 5.67 * 0.45 T^4 = 100 Ts + 5.67 * **0.42** Ts^4

Let Ts = 20C. We find T = about 16.436C < Ts
RHS = 100 * 2.9315 + 5.67 * 0.42 * 2.9315^4 = 293.15 + 5.67 * **0.42** * 73.8515
= 293.15 + **175.8701** = 469.020073
LHS = 100 * 2.8959 + 5.67 * 0.45 * 2.8959^4 = 289.586 + 5.67 * 0.45 * 70.3250
= 289.586 + 179.4342 = 469.020099, checks

Qc = k(T - Ts) = 100 * (2.8959 - 2.9315) = - 3.565 out or +3.565 in
Qr = 5.67 * (α εs Ts^4 - αs ε T^4) = 5.67 * (0.6***0.7** * 2.9315^4 - 0.9*0.5 * 2.8959^4)
= 5.67 * (**0.42** * 73.8515 - 0.45 * 70.3250) = 5.67 * (**31.0176** - 31.6462) = - 5.67 * 0.62859 = - 3.564, in or +3.564 out. Close to Qc, round-off.

The minus signs mean heat transfers out by conduction and in by radiation, at same rates.

Note radiator T = 16.436 < surroundings Ts = 20, so conduction is from warm surroundings to cold radiator. But cold radiator, T = 16.436, transfers radiant energy to warmer surroundings, Ts = 20, because α εs < αs ε, 0.6*0.7 < 0.9*0.5. Qr = Qc = - 3.564. Since surroundings emit with lower intensity, rates drop and radiator cools.

If T = Ts = 20, Qc = 0 and

Qr = 5.67 * (α εs Ts^4 - αs ε T^4) = 5.67 * (0.6***0.7** * 2.9315^4 - 0.9*0.5 * 2.9315^4)
= 5.67 * (**0.42** - 0.45) * 2.9315^4 = 5.67 * (- 0.03) * 73.8515 = - 5.67 * 0.6286 = - 12.562 in or 12.562 out. This is an unsteady-state.

This means radiant energy is going out but no thermal energy is coming in. This is not a steady-state situation. The radiator T = 20 will decrease, thermal energy starts to go out and incoming radiant energy decreases until a T = 16.436 is reached. Qr in drops from - 12.562 to - 3.564 and Qc out increases from 0 to - 3.565, constant.

At steady state, radiator is T = 16.436 and surroundings Ts = 20. Energy is transferring in by conduction because T < Ts. Energy is transferring out by radiation because intensity of warmer surroundings < radiator surface.

Qr = 5.67 (0.6***0.7** * 2.9315^4 - 0.9*0.5 * 2.8959^4) = 5.67 * (0.42 * 73.8515 - 0.45 * 70.3251) = 5.67 * (**31.0176** - 31.6463) = 5.67 * (- 0.6286) = -3.564.

Radiant energy transfers out to surroundings at - 3.564 even though surroundings Ts = 20 are warmer than radiator at T = 16.436.

Since radiation rate increases as power of 4, as conduction rate increases linearly, there will always be a solution where Qr increases and Qc decreases until they meet, Qc = Qr = - 3.564, not = 0. Ts remains 20C and radiator cools to 16.436 at equilibrium.

With simultaneous energy transfer by conduction and radiation between a body and its surroundings at steady-state, radiant energy always transfers from the colder to the warmer because energy transfers by conduction from the warmer to the colder. This is true in the atmosphere at Earth's surface.

Confusion

Many err claiming radiant energy cannot transfer from the colder radiator to the warmer one, heating it further, because they incorrectly assume the driving force (at a distance) is temperature difference, which is true for conduction/convection through a matter field, while the driving forces for radiant energy transfer between radiators are intensity differences at radiator surfaces through a radiation field. As proved by Martin Hertzberg[15].

Radiant energy does not transfer due to a temperature difference at a distance. Temperature is a point property of matter proportional to the kinetic energy of its atoms and molecules. The transfer directions switch at T = Ts, when Qc = Qr. Radiation direction is always opposite to conduction direction according to the First Law.

So when surroundings are Ts, a room wall at T can be greater or less than Ts, depending on its radiating properties compared to radiating properties of surroundings. Rate in by conduction = rate out by radiation = a nonzero constant at different temperatures, unless Kirchhoff's Law applies. When it does the temperatures are equal and no energy transfers between the radiator and surroundings either way.

Atmosphere

Since atmospheric temperature decreases with altitude, why doesn't energy transfer up by conduction, equalizing T above? Because thermal energy indicated by T, is kinetic energy of molecular motion and it must decrease as potential energy increases with altitude in Earth's gravitational field to maintain fixed total energy of each m^3 of gas. Another energy mechanism is involved.

Some popular explanations of Green House Gas Theory say radiant energy transfers from cold atmospheric CO2 down to warmer surface, which absorbs it, warming it further, i. e. global warming. Actually surface partly radiates directly to space because atmosphere has some transmissivity and the rest is absorbed by the atmosphere, including trace 400 ppm CO2, and then reemitted to space.

A recent paper[2] derived rigorous equations for the coupled atmosphere and surface temperatures. Only system properties are needed, no empiricism. When one warming and three cooling mechanisms are included in the whole system, the net effect of CO_2 on temperature is small and likely < 0.

The remaining question to quantify the effect of CO_2 changes on temperatures is: how much does CO_2 affect the atmosphere's radiating properties: absorptivity and emissivity? Assuming[2] a 1% increase in the atmosphere's radiating properties, perhaps due to increased CO_2, surface temperature change is - 0.76C and atmosphere change is -0.39C. The net effect is slight cooling.

Applying (3) we see Qr > 0 for transfer from surface up to and absorbed by atmosphere, even when Ts > Ta. That is because there is no conduction involved, as proved above. The presence of radiating CO_2 increases atmosphere emissivity, a resistance to radiant energy transfer. CO_2 is not an energy blocker or trapper; it is an absorber and transmitter. No radiant energy transfers from cold atmosphere with CO_2 down to warm surface, warming the surface.

A shiny white car has greater reflectivity than rough black car. So it has lower absorptivity and emissivity. Since white absorbs less radiant energy than black, it emits less, causing it to be cooler.

Increase Ts case
Surroundings warm up.
Assume αs = 0.9, εs = 0.8, α = 0.6, ε = 0.5 as before.

Let Ts = 30C. We find T = about 33.688C > Ts
RHS = 100 * **3.0315** + 5.67 * 0.48 * 3.0315^4 = **303.15** + 5.67 * 0.48 * **84.4560**
= 303.15 + **229.8553** = 533.005334
LHS = 100 * **3.06838** + 5.67 * 0.45 * $\mathbf{3.06838^4}$ = **306.838** + 5.67 * 0.45 * **88.6414**
= 306.838 + 226.1685 = 533.006515, checks

Qc = k(T - Ts) = 100 * (3.06838 - 3.0315) = 3.688 out
Qr = 5.67 * ($\alpha\ \varepsilon s\ Ts^4$ - $\alpha s\ \varepsilon\ T^4$) = 5.67 (0.6*0.8 * $\mathbf{3.0315}^4$ - 0.9*0.5 * $\mathbf{3.06838}^4$
= 5.67 * (0.48 * **84.4560** - 0.45 * 88.6414) = 5.67 * (**40.5387** - **39.8886**) = 5.67 * **0.65023** = 3.6868 in. Close to Qc, round-off.

Note radiator T > surroundings Ts, but colder surroundings transfer radiant energy into warmer radiator, heating it because α εs > αs ε, 0.6*0.8 > 0.9*0.5. T – Ts increases from 3.473 to 3.688 or + 0.215C when Ts increases from 20 to 30C.

Put one hand on a mirror or metal faucet and the other on a fiberboard wall. The wall is warmer because it is a better absorber/emitter. Mirror and metal are better reflectors.

Table of Solutions

α	ε	αs	εs	α εs	αs ε	Ts	T	T - Ts

0.4	0.2	0.8	0.4	0.16	0.16	20	20.000	0.000
0.6	0.5	0.9	0.8	0.48	0.45	---	23.473	3.473
0.9	0.8	0.6	0.5	0.45	0.48	---	16.600	- 3.400
----	----	----	0.7	0.42	----	---	16.436	- 3.5641
----	----	----	0.8	0.48	----	30	33.688	3.6877

Radiation Only

In a vacuum there is no conduction, k = 0. Qc = 0 = Qr and $\alpha\ \varepsilon s\ Ts^4 = \alpha s\ \varepsilon\ T^4$.

Given Ts we find $T^4 = (\alpha\ \varepsilon s / \alpha s\ \varepsilon)\ Ts^4$.

$T = (\alpha\ \varepsilon s / \alpha s\ \varepsilon)^{0.25}\ Ts$.

If $(\alpha\ \varepsilon s / \alpha s\ \varepsilon) > 1$, T > Ts.

Let $T = (0.48 / 0.45)^{0.25}\ Ts = 1.016265 * Ts$.

If Ts = 20, T = 1.016265 * 2.9315 = 2.97918 = 24.768C

This means steady-state temperature, T, of a radiator in vacuum can differ from its radiating surrounding temperature, Ts, with no energy transferring in or out. It radiates with same intensity as surroundings.

Conclusion. According to the First Law of Thermodynamics, radiant energy transfers from a cold to a warmer radiator in the presence of energy transfer by conduction the other way. The temperature difference between radiators at steady-state depends on their radiating properties: absorptivity and emissivity.

This paper is not a mere theory because it is based on well-known laws of physics and mathematics, confirmed by observation.

Appendix. Derivation of General Radiant Energy Transfer Law Between Two Radiators[1]

First, we employ the basic law for intensity of all radiators, the Stefan – Boltzmann Law.

$$\mathbf{I,\ w/m^2 = 5.67\ \varepsilon\ T^4} \qquad (4)$$

where ε is the emissivity of the radiator and T = K/100 and K is radiator temperature, deg Kelvin. Like absorptivity, emissivity has a spectrum of intensity vs. wavelength unique to each atom and molecule.

Earth's surface entities are taken to be at some average temperature, T(h), and to have an average emissivity of e(h) and an average absorptivity of a(h). The gaseous atmosphere, without clouds to begin with, is approximated as two concentric layers that are partially absorbing, *partially transparent, and non-reflective. The lower plate, closest to the Earth's surface represents the bulk of the atmosphere and it is optically thick in the major absorption bands of its gaseous components. The upper plate is the optically thin part of the atmosphere from which infrared radiation from those bands is lost to free space. The lower, denser atmospheric level has an average temperature of T(c), an average absorptivity of a(c), and an average emissivity of e(c). The upper, less dense portion of the atmosphere is optically thinner with an average temperature of T(t), and average absorptivity of a(t), and an average emissivity of e(t).*

If the hotter Earth's surface were facing a complete void at 0 K, the flux of radiant energy that it would emit to that void would be:

$$e(h)\ \sigma\ T(h)^4 \qquad (1)$$

where σ is the Stefan-Boltzmann constant. Similarly, if the colder atmosphere were facing such a void, the flux of radiant energy that it would emit to that void would on the average be:

$$e(c)\ \sigma\ T(c)^4 \qquad (2)$$

When they are facing each other as they are on the Earth, the colder atmosphere absorbs a flux of radiation emitted from the hotter Earth surface of:

$$a(c)\ e(h)\ \sigma\ T(h)^4 \qquad (3)$$

The warmer earth then absorbs a flux of radiation emitted from the colder atmosphere of:

$$a(h)\ e(c)\ \sigma\ T(c)^4 \qquad (4)$$

…. the net transfer of the radiant energy flux between the two surfaces is:

(3) - (4): $I(net) = a(c)\ e(h)\ \sigma\ T(h)^4 - a(h)\ e(c)\ \sigma\ T(c)^4,\ \sigma = 5.67$

$$\mathbf{I(net) = 5.67\ [a(c)\ e(h)\ T(h)^4 - a(h)\ e(c)\ T(c)^4]} \qquad \mathbf{(5)}$$

This general case is true without invoking the special case of Kirchhoff's Law, e(h) = a(h) or e(c) = a(c), which is only valid when the radiator has no non-radiant energy transfer mechanisms affecting it, like thermal and convective heat transfer, condensing, melting, electrical, magnetic, chemical, mechanical and gravitational energy transformations.

Example 1. General. Neither radiator follows Kirchhoff's Law.
T(h) = 275/100
T(c) = 274/100
a(c) = 0.4
a(h) = 0.6
e(h) = 0.3
e(c) = 0.5

$I(net) = \sigma\ [0.4 * 0.3 * 2.75^4 - 0.6 * 0.5 * 2.74^4]$
$I(net) = \sigma\ [0.12 * 2.75^4 - 0.3 * 2.74^4]$
I(net) = σ [0.12 * 57.191 - 0.3 * 56.364]
I(net) = σ [6.863 - 16.909]
$I(net) = 5.67\ [- 10.0462] = - 56.962\ w/m^2$
This means radiant energy flows from 274K radiator to 275K radiator.

Example 2. Only cold radiator obeys Kirchhoff's Law, hot does not.
T(h) = 275/100
T(c) = 274/100
a(c) = 0.5
a(h) = 0.6
e(h) = 0.3
e(c) = 0.5

I(net) = σ [0.5 * 0.3 * 2.75^4 - 0.6 * 0.5 * 2.74^4]
I(net) = σ [0.15 * 2.75^4 - 0.3 * 2.74^4]
I(net) = σ [0.15 * 57.191 - 0.3 * 56.364]
I(net) = σ [8.579 - 16.909]
I(net) = 5.67 [- 8.331] = - 47.234 w/m^2
This means radiant energy flows from 274K radiator to 275K radiator.

Example 3. Both radiators obey Kirchhoff's Law
T(h) = 275/100
T(c) = 274/100
a(c) = 0.5
a(h) = 0.6
e(h) = 0.6
e(c) = 0.5

I(net) = σ [0.5 * 0.6 * 2.75^4 - 0.6 * 0.5 * 2.74^4]
I(net) = σ [0.3 * 2.75^4 - 0.3 * 2.74^4]
I(net) = σ [0.3 * 57.191 - 0.3 * 56.364]
I(net) = σ [17.157 - 16.909]
I(net) = 5.67 [- 8.331] = + 0.248 w/m^2
This means radiant energy flows from 275K radiator to 274K radiator.

In this special case where Kirchhoff's Law applies, the rate law simplifies to the one commonly used by GHGT theorists.

$$\mathbf{I(net) = \sigma\, a(c)\, e(h)\, [T(h)^4 - T(c)^4] = \sigma\, a(h)\, e(c)\, [T(h)^4 - T(c)^4]} \quad \mathbf{(5)}$$

So the Hertzberg general rate law disproves the notion radiant energy transfer only flows from the hot radiator to the cold one. That is only true if one radiator is sufficiently hotter than the other or both radiators obey Kirchhoff's Law, emissivity = absorptivity. That is not easy to guarantee. The Earth's atmosphere has several energy transfer mechanisms within it and hence does no obey Kirchhoff's Law.

References

1. Hertzberg, M, "The Night Time Radiative Transport Between the Earth's Surface, Its Atmosphere, and Free Space", *Energy & Environment*, V23, n5, 2012, p 821. http://climaterealists.com/attachments/ftp/05-Hertzberg.pdf
2. Latour, PR, "Radiation Physics Laws Give the Effect of CO2 on Earth's Temperatures – A Primer", *Principia Scientific International*, February 25, 2017. http://principia-scientific.org/radiation-physics-laws-give-effect-co2-earths-temperatures-primer/