Measurement of radiation losses over thermal ground using a calorimeter

M.P. HOCHSTEIN[1]
Geothermal Institute, University of Auckland, Auckland, New Zealand

C.J. BROMLEY[2]
GNS Science, Wairakei Research Centre, Taupo, New Zealand

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Full addresses/phone/fax/email

[1]Geothermal Institute, University of Auckland, Private Bag 92019, Auckland, New Zealand
(mm.hochstein@clear.net.nz)
[2]GNS Science, Wairakei Research Centre, Private Bag 2000, Taupo 3377, New Zealand
Ph. (07) 374 8211 Fax (07) 374 8199 (c.bromley@gns.cri.nz)

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MEASUREMENT OF RADIATION LOSSES OVER THERMAL GROUND USING A CALORIMETER

M.P. HOCHSTEIN[1], C.J. BROMLEY[2]

[1]Geothermal Institute, University of Auckland, Auckland, New Zealand
[2]GNS Science, Wairakei, New Zealand

SUMMARY - The total (q_{tot}) and convective (q_{conv}) fluxes at the surface of thermal ground can be measured with a ground calorimeter. The difference ($q_{tot} - q_{conv}$) at a given site equals the subsurface conductive flux (q_{cond}) which at the surface splits into a surface conductive ($q_{0\ cond}$) and a radiation (q_{rad}) component. The anomalous radiation flux (Δq_{rad}), with respect to ambient temperature, can be assessed by separating the meter from the ground using a small air gap. Measurements over the Karapiti steaming ground field (Wairakei, NZ) have shown that the ratio ($\Delta q_{rad} / q_{tot}$) is independent of (q_{tot}). The measurements at 15 sites point to a ratio ($\Delta q_{rad} / q_{tot}$) of 0.22 +/- 0.06 which implies that at least c. 1/5 of the total flux is transferred from thermal ground to the calorimeter by radiation. The ratio is slightly larger if the IR reflectance of the calorimeter bottom (about 0.2) is considered.

1. INTRODUCTION

Heat flow measurement at the surface of 'steaming' ground over high temperature geothermal systems involves assessment of convective, conductive, and radiation fluxes (Hochstein and Bromley, 2007). The total flux (**q_{tot}**) and the convective flux (**q_{conv}**), associated with the rising of minor steam, can be measured with a water-filled ground calorimeter. The shallow subsurface conductive flux (**q_{cond}**) can be obtained from the difference of the two. At the surface it splits into a radiation component (**Δq_{rad}**) and an air heating component (**$q_{0\ cond}$**) which were not separately assessed when the first detailed heat flow measurements over hot ground were made (Hochstein and Bromley, 2005).
Recent modification of the survey procedure allows an assessment of the anomalous radiation flux component $\Delta' q_{rad}$ which equals Δq_{rad} if the calorimeter temperature T_c is close to ambient air temperature T_a. The total anomalous radiation loss of thermal ground can be assessed from spatial $\Delta' q_{rad}$ and q_{tot} data. All measurements of $\Delta' q_{rad}$ in this study were made at sites within the Karapiti steaming ground field (Wairakei Field, New Zealand) where detailed total and convective flux measurements have already been collected (Bromley and Hochstein, 2005).

2. HEAT TRANSFER OF HOT AND STEAMING GROUND

The heat flux components involved in the heat transfer of q_{tot} at the surface of thermal ground are shown in Fig.1 and include:

i) Convective heat transfer by minor steam permeating through the surface (the q_{conv} component); this is proportional to the rate of condensation at the calorimeter bottom.

ii) Conductive transfer through a thin, near-surface soil layer with an anomalously high temperature gradient ($\Delta T/\Delta z_0$); at the surface, this converts into direct heating of the convecting air mass and radiation losses.

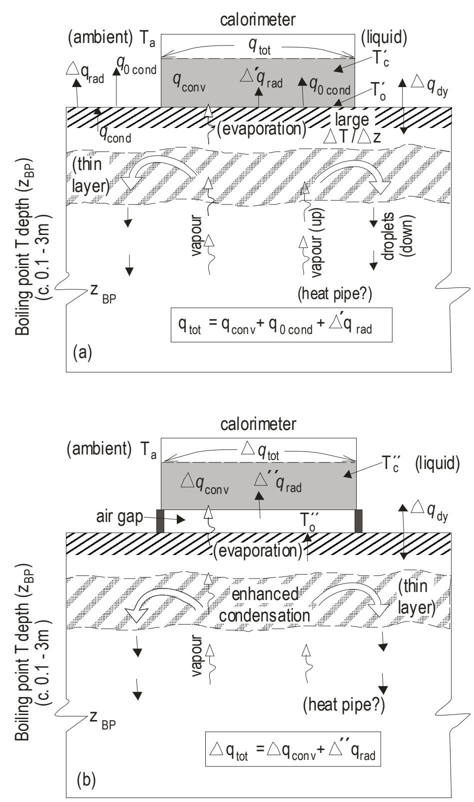

Figure 1. Set-up of calorimeter over thermal ground for measurement of (a) total flux and convective (steam) flux and (b) IR component.

iii) Heat transfer by anomalous radiation (Δq_{rad}); this is given by the difference in radiation flux (for unit area) over thermal ground with an elevated surface temperature T_0, and that over surrounding non-thermal ground with an ambient temperature T_a.

There are other time-variable parameters which affect the magnitude of the various heat flux components. The conductive component q_{cond}, for example, contains a time-variable component Δq_{dy} caused by changes in daily surface temperatures. These are controlled by incoming and outgoing short and long-wave radiation fluxes which affect the near-surface temperature gradient ($\Delta T/\Delta z_0$) and the surface temperature T_0, thus contributing to the anomalous radiation component.

All heat flux modes listed refer to specific heat fluxes (unit: W/m^2); all flux components are time-variable parameters, including Δq_{rad} and $\Delta' q_{rad}$. The effect of time-variable disturbances can be reduced if measurements are made during dry periods in the summer and during the same daily hours under overcast conditions.

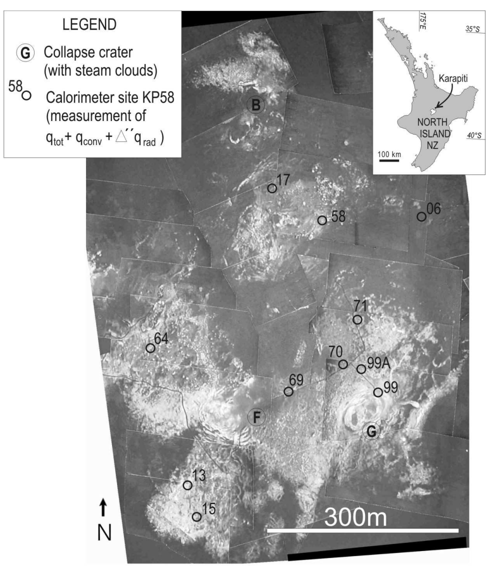

Figure 2. Location of (IR) calorimeter sites occupied in 2006/7 using a grey-tone IR mosaic of the Karapiti Field taken in 2000 as a base map.

Photo-mosaic images of an infrared (IR) airborne survey of the Karapiti field are shown in Fig.2. It outlines the area where, during 2006 and 2007, we measured the anomalous radiation flux on the ground at selected sites (also shown in Fig.2). To obtain the mosaic pattern in Fig.2, the emissive radiation (q_{rad}), observed from the air in the 8 to 12 µm waveband, was converted to a grey tone scale of apparent surface temperatures ($T_{0\ app}$). These are difficult to interpret in terms of heat loss and heat transfer because of the lack of representative, true ground temperature data and the combined masking effects of vegetation and wafting steam (Bromley and Hochstein, 2005). The apparent temperature at the top of large steam clouds occurring, for example, over collapse craters (labelled in Fig.2) are only a few degrees C above T_a and cannot be used to assess the heat discharged by these manifestations (Hochstein and Bromley, 2001). However, IR airborne surveys are useful for monitoring changes in surface extent and have become an important surveillance tool at Karapiti (Mongillo et al., 1993; Bromley and Hochstein, 2000). To obtain information about the actual heat transfer by radiation, in relation to other forms of heat transfer, measurements have to be made on, or close to, the surface of the hot ground.

3. MEASUREMENT OF THE RADIATION FLUX COMPONENTS ON THERMAL GROUND

When placing a water-filled calorimeter on thermal ground with a surface temperature T_0, the heat flux through its bottom plate is given by:

$$q_{tot} = q_{conv} + (q_{0\ cond} + \Delta' q_{rad}). \qquad (1)$$

The components q_{tot} and q_{conv} can be measured directly and are given by the rate of temperature rise in the calorimeter and the condensation rate of steam at its bottom respectively (Hochstein and Bromley, 2005). The term ($q_{0\ cond} + \Delta' q_{rad}$) equals the subsurface conductive flux (q_{cond}) given by the sum of the conductive flux $q_{0\ cond}$ that directly heats the air, and the radiation flux component $\Delta' q_{rad}$, which was neglected in our earlier studies. The radiation flux entering the bottom of the calorimeter is controlled by the Boltzmann Law for heat transfer by radiation between two plates:

$$\Delta' q_{rad} / F = \varepsilon_1 \sigma T_0^4 - \alpha_{12} \sigma T_c^4 \quad \text{(with } T_0 > T_c\text{)}, \qquad (2)$$

where ε_1 is the 'emittance' of thermal ground, α_{12} the 'absorptance' of the bottom of the calorimeter, T_0 the mean ground surface temperature (in K), and T_c the temperature of the calorimeter bottom; σ is the Stefan Boltzmann constant 0.567×10^{-9} [W m^2/ K^4], and F the 'view factor' (Perry and Chilton, 1973). Equation (2) can also be used to define an anomalous radiation flux Δq_{rad} with respect to the radiation flux associated with surrounding ambient ground.
The conductive component $q_{0\ cond}$ in equation (1) can be significantly reduced if flux measurements are made by separating the calorimeter from the ground by a small air gap (see Fig.1b). Only a fraction of the total flux (Δq_{tot}) will then be measured which contains a fraction of the convective flux Δq_{conv}, the radiation flux $\Delta'' q_{rad}$ and a residual conductive flux $\Delta q_{0\ cond}$

Deleted:

$$(\Delta q_{tot}) = \Delta q_{conv} + \Delta'' q_{rad} + \Delta q_{0cond} \quad (3)$$

The residual conductive flux Δq_{0cond} that occurs during calorimeter measurements within the air-steam mixture in the covered air gap (assuming there is no convective air movement) is small, because of the low thermal conductivity of air and steam. It was estimated to lie between 3 and 15 W/m^2 for sites with q_{tot} between 100 and 1100 W/m^2 respectively. The Δq_{0cond} component will therefore be neglected in the following.

If the Δq_{tot} measurements (Fig.1 b) are made before the q_{tot} measurements (Fig.1 a), and this was our preferred sequence, its $\Delta'' q_{rad}$ value will be slightly greater than $\Delta' q_{rad}$ since the average surface temperature T_0 usually decreases during the measurements. Thus all parameters in equation (1) can be measured or assessed. The components $\Delta' q_{rad}$ and $\Delta'' q_{rad}$ are associated with an average ground temperature T'_0 and T''_0 and an average calorimeter (water) temperature of T'_c and T''_c respectively (Fig.1).

4. OBSERVED DATA

Assessment of $\Delta'' q_{rad}$ in the field involves measurement of the flux components Δq_{tot} and Δq_{conv} (equ. 3). To cancel the conductive flux q_{0cond}, the calorimeter was placed at each site on a thin plastic ring (2 cm height of air gap) and the diminished fluxes Δq_{tot} and Δq_{conv} were obtained by monitoring the heating rate of the calorimeter and the rate of steam condensation at the bottom of the calorimeter respectively. It was assumed that the steam flux associated with q_{conv} was constant during the measurements taken on the ring and on the ground.

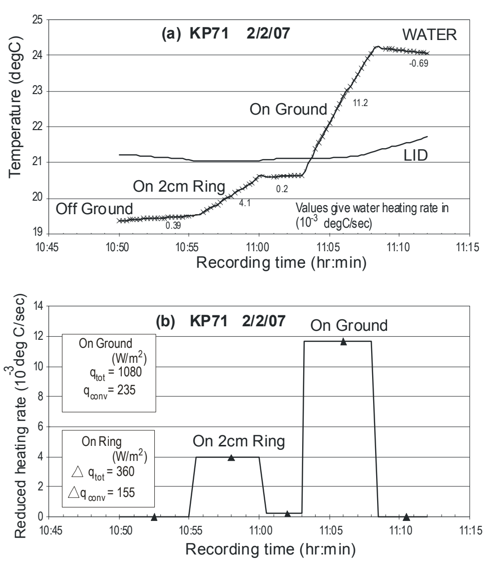

Figure 3. (a) Calorimeter recording of heating rates at site KP 71; (b) Plot of drift reduced heating rates at site KP 71.

The results at a selected station (KP 71) are shown in Fig.3 where the recorded calorimeter (water) temperature is plotted versus recording time. The cycle shown in Fig.3 was used at all sites. For drift control, the calorimeter temperature T_c was monitored on a thermally insulated block during three periods at the beginning, the middle, and the end of the cycle. At the midpoint of these periods, the ground temperatures T_0 were measured; the near-surface soil temperature gradient was usually obtained during the first rest period. The condensates at the calorimeter bottom were collected when it was removed from the ring or hot ground respectively. The cycle included measurement of ambient air temperature (T_a) and monitoring of the lid temperature of the calorimeter. Allowing for a small temperature drift, reduced water heating rates are obtained (listed in Fig. 3 a). These can be converted to the flux components Δq_{tot} and q_{tot} ; likewise, normalised condensation rates are obtained yielding Δq_{conv} and q_{conv}. Using the balance equations (1) and (3), the unknown parameters (q_{0cond} + $\Delta' q_{rad}$) and $\Delta'' q_{rad}$ can be found.

Most observed and derived flux data contain uncertainties and errors; the average relative error ($\Delta q/q$) of q_{tot} and q_{conv} , for example, is c. 10% each (Hochstein and Bromley, 2005). The errors of ambient air temperature T_a and average calorimeter temperatures T'_c and T''_c are < 0.5 deg C. The uncertainty of the mean ground temperatures T'_0 and T''_0, however, is greater and is proportional to their standard deviation (between 1 and 3 deg C). An advantage of using a ground calorimeter in assessing radiation flux is that the device allows measurement of the radiation energy integrated over all radiation wavelengths.

Coherency of the measured flux data can be checked by considering the dimensionless ratio:

$$R'' = (\Delta q_{tot} - \Delta q_{conv}) / (q_{tot}) = \Delta'' q_{rad} / q_{tot} \quad (4)$$

which allows an assessment of the fraction of total heat lost by anomalous radiation. A plot of q_{tot} versus R'' is shown in Fig.4; it indicates that the ratio R'' is independent of q_{tot}. The average value of R'' (0.22 +/- 0.06) implies that c. one fifth of the total flux is transferred by anomalous radiation. The four, apparently anomalous R'' values in Fig.4 occur at sites where $T'_0 > T''_0$, that is at sites where the average ground temperature T_0 increased during the measurements. To obtain the R' value, the anomalous flux $\Delta'' q_{rad}$ has to be reduced to $\Delta' q_{rad}$ which entered the calorimeter towards the end of the measurement cycle.

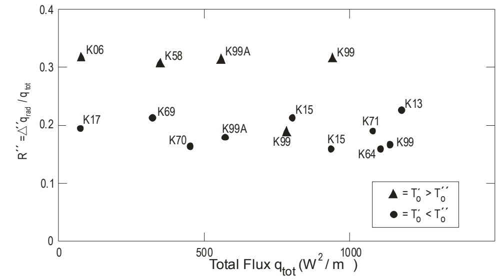

Figure 4. Plot of observed total flux q_{tot} versus ratio R" = (Δ"q_{rad} / q_{tot}).

5. COMPUTING THE RADIATION FLUX OF THERMAL GROUND

The radiation flux entering the bottom of the calorimeter can be assessed by using the Boltzmann Law, see equation (2). It contains site-specific parameters, such as ground emissivity, average surface temperature T_0, and equipment-specific parameters, for example, the absorptance α_{12} of the calorimeter bottom, the mean calorimeter (water) temperature T_c, and a view factor F if the meter is raised above the ground (Hochstein and Bromley, 2007). Climatological parameters, such as soil evaporation, humidity, and surface net radiation (Eymard and Tacomet, 1995), are neglected since only the anomalous flux Δq_{rad} with respect to adjacent ground with a mean ambient temperature T_a has to be assessed.

5.1 Assessment of uncertainties and site-specific parameters

Several tests were made to obtain representative ground temperatures T_0 before, in between, and after placing the calorimeter on thermal ground. Initially, we used a calibrated thermocouple probe (FLUKE digital thermometer) to measure T_0 at the centre of the area covered by the calorimeter. Later, the surface temperatures were measured using a five point grid pattern and checked by a calibrated IR- thermometer (RAYTEK – Rayner ST -'IR-gun'). It was found that T_0 of hot ground can vary significantly over small distances (even a few cm) owing to different, concealed diffuse steam leakage near the surface. Single spot T_0 values were inadequate to assess Δq_{rad} but even average (5 point) T_0 values can differ between thermocouple and 'IR-gun' data. The thermocouple data over ground with high T_0 values are often disturbed since the tip of the probe can indent the surface. At 10 out of 15 sites the average temperature T_0 decreased during the measurement cycle, at 5 sites it increased with time (see Fig.4). Allowing for error propagation, it was found that the standard deviation σ of the interpolated mean ground temperatures T'_0 and T''_0 reaches values up to 4 ^oC at a few sites. Site KP 71, for example, was such a site with: T''_0 = 35.2 +/- 3.9 ^oC; T'_0 = 33.6 +/- 4.0 ^oC, T_a = 18 ^oC. Ground temperatures measured with the IR-gun were found to be the better data set; for older surveys, temperatures measured with the thermocouple and using the near- surface temperature gradient were considered to be the second best data set.

The emissivity ε_1 of exposed thermal ground is usually taken to be between 1 (vegetation cover) and 0.9 (bare ground) when interpreting aerial IR data observed within the 8 to 14 µm wavelength window (Schmugge, 2005). For broadband radiation, as measured with our ground calorimeter, soil moisture content can affect spectral emissivity. For this study it was assumed that ε_1 of thermal ground is 0.95.

5.2 Equipment-specific parameters

The temperature T_c of the thin bottom plate of the calorimeter is well-defined since it equals that of the stirred water mass inside the vessel and is recorded continuously (see Fig. 3a). Errors of the mean bottom temperatures T'_c and T''_c are less than 0.5 ^oC.

The value of 'absorptance' α_{12} of the stainless steel bottom is not known. Values between 0.4 and 0.65 have been quoted for this material using a laser beam (Bergstroem et al., 2007); older studies by Wieting and DeRosa (1979) quote values as low as 0.1 for 304 type stainless steel. Condensation of vapour, the rough ground surface, and possible traces of clay at the bottom plate when collecting the condensates would all increase absorptance of the stainless steel bottom which therefore would attain characteristics of a 'grey body'. A good fit value of α_{12} = 0.8 was obtained when computing radiation losses using equation (3) retaining α_{12} as parameter and reducing the difference between observed and computed $\Delta''q_{rad}$ values to a minimum for the middle range of Δq_{rad} fluxes between 100 and 200 W/m^2. It is also possible that the absorptivity of the calorimeter differs between measurements taken on the ring and later on the ground. A value of 0.8 for α_{12} implies a 'reflectance' of (1- α_{12}) = 0.2, i.e. the fraction of IR radiation which is reflected back into the ground. Hence, about 80% of the IR radiation from hot ground entered, on average, the calorimeter.

The error in selecting the appropriate view factor F is small. When placed on the ground, F is close to one; when lifted off the ground (with a separating air gap of thickness h), F decreases. For h = 2 cm and 2r = 24 cm, F is c. 0.95 (Perry and Chilton, 1973).

5.3 Computing $\Delta''q_{rad}$, $\Delta'q_{rad}$, and R'

Using the site-specific parameters (i.e. ε_1 = 0.95; T''_0) and the equipment-specific parameters (i.e.

α_{12} = 0.8; T''$_c$), a 'theoretical' anomalous radiation flux Δq_{rad} was computed using equation (3) and compared with the observed $\Delta'' q_{rad}$ flux. The scatter of the data points has affinity with the scatter of heat flux data derived from airborne data when compared with observed surface fluxes (Eymard and Taconet, 1995).

A sensitivity analysis showed that the uncertainty in emissivity values does not significantly affect the computed flux values. Errors in the observed T''_0 data and uncertainties in the measured flux values have greater effects. The most significant effect, however, is that caused by the uncertainty in the absorptance α_{12} and the assumption that it remains constant during the measurements. When the calorimeter was in contact with the ground, $\Delta' q_{rad}$ values can be assessed using the T'_0 and T'_c data set, yielding a new ratio R'= $\Delta' q_{rad} / q_{tot}$. Since, for two thirds of the stations, the average ground temperature T_0 decreased during the measurement cycle, the inferred $\Delta' q_{rad}$ value decreased slightly in comparison to $\Delta'' q_{rad}$ (for station KP 71 shown in Fig.3, it decreased, for example, from $\Delta'' q_{rad}$ = 205 W/m^2 to $\Delta' q_{rad}$ = 185 W/m^2). The ratio R' was found to be 0.20 +/- 0.06, i.e. c.. 10 % less than R''.

5.4 Checking the (q_{conv} / q_{tot}) ratio Q'

Coherency of the convective flux data q_{conv} can be checked by computing the q_{conv} / q_{tot} ratio (Q'). A plot of q_{tot} versus Q' is shown in Fig.5.

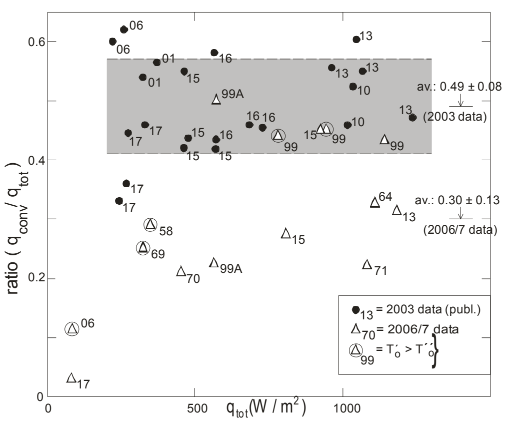

Figure 5. Plot of observed total flux q_{tot} versus ratio Q' = (q_{conv} / q_{tot}); including results from the 2006/7 and 2003 surveys. Note that data labels refer to different site locations (eg. Fig. 2).

The scatter of the 2006/7 data is rather large; convective fluxes q_{conv} for q_{tot} < 200 W/m^2 are very low causing anomalously low Q' values. A similar result was found during previous studies (Hochstein and Bromley, 2005). However, the scatter of Q' in the 2003 data is significantly lower (taken from Table 2 in Hochstein and Bromley, 2005); these data are also shown in Fig.5. It appears that about two thirds of the Q' values of the 2006/7 survey are relatively low in comparison with the Q' values of the 2003 survey. This points to reduced q_{conv} fluxes in the 2006/7 survey, possibly caused by the different measurement sequence which can impact on the subsurface vapour flux (during the 2003 survey the calorimeter was first placed on the thermal ground whereas during the 2006/7 survey it was first placed on the ring).

6. DISCUSSION AND SUMMARY

Measurements of the total heat flux q_{tot} and its radiation (Δq_{rad}) and convective (q_{conv}) flux components over the Karapiti steaming ground area have shown that the IR radiation component contributes on average at least c. 22 % to the total heat lost from hot and steaming ground. The flux components were measured with a ground calorimeter with an IR acceptance (α_{12}) of c. 80 % of the total anomalous radiation coming from hot ground. The fraction (Δq_{rad} / q_{tot}) is independent of the magnitude of the total flux. In an earlier paper, using data measured prior to 2006, an estimate of c. 15% was quoted for (Δq_{rad} / q_{tot}) (Hochstein and Bromley, 2007); the new value of c. 22% is based on data from separate new surveys undertaken between 2006 and 2007. If the IR reflectance of the calorimeter bottom is indeed c. 20 % , this implies that, on average, the total radiation component could be greater (up to 28 %) than that observed. Some modification of the calorimeter is therefore required to reduce its reflectance (using black coating for example).

Assuming that evaporation arises from the saturated, near-surface soil layer, the resulting convective flux q_{conv} should dominate the surface conductive flux q_{0cond} , according to an evaporation study of water surfaces (Ryan et al., 1974). The average Q' value (plus 1 standard deviation) of the 2003 survey (in Fig.5) indicates that c. 50 % of the total flux over hot and steaming ground is by convective flux $q_{conv.}$ On balance, convective flux is certainly significant, and may be the dominant surface flux component (at least for q_{tot} > 200 W/m2). Additional tests of the measurement cycles is still required aiming at a reduction of errors in the convective flux during future IR studies.

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