



Combined thermal imaging and radiative modelling for temperature reconstruction of a CO₂ plasma jet

Downloaded from: <https://research.chalmers.se>, 2026-10-30 13:20 UTC

Citation for the original published paper (version of record):

Gunnarsson, A., Mishra, S., Qasim, I. et al (2026). Combined thermal imaging and radiative modelling for temperature reconstruction of a CO₂ plasma jet. Proceedings of the Combustion Institute, 42. <http://dx.doi.org/10.1016/j.proci.2026.106690>

N.B. When citing this work, cite the original published paper.



Combined thermal imaging and radiative modelling for temperature reconstruction of a CO₂ plasma jet

Adrian Gunnarsson^{*}, Saumitra Mishra, Ibrahim Qasim, Klas Andersson

Department of Environmental and Energy Sciences, Chalmers University of Technology, Sweden

ARTICLE INFO

Keywords:

CO₂ plasma
Thermal imaging
Radiative heat transfer
Spectral gas radiation modelling

ABSTRACT

To mitigate greenhouse gas emissions, high-temperature industries must transition toward electrified and more sustainable heating technologies. For some processes, replacing fossil-fired burners with plasma-based heat sources is promising but requires careful small-scale evaluation. In this work, radiative characteristics of a 50 kW_{el} non-transferred CO₂ plasma torch operating in open air are investigated using thermal infrared imaging and radiative intensity measurements. The two measurements are combined with detailed spectral modelling of the gas radiation to reconstruct the temperature distribution within the plasma jet. The model accounts for emission and absorption by CO₂ and CO within the broadband range of the radiative intensity measurement (0.1–100 μm) as well thermal camera's detection range (6.8–17 μm) and accounts for the spectral properties of the optics and detector sensitivity. The modelled photon flux incident on the camera sensor is converted into equivalent units of digital counts and compared to measurements. A supporting CFD analysis indicates significant CO₂ dissociation near the plasma torch exit and air entrainment downstream, both of which reduce optical thickness and help interpret discrepancies between measured and modelled IR signals. Sensitivity analysis shows that background reference levels and gas composition exert stronger influence on IR counts than on broadband intensity. Results demonstrate that thermal imaging, combined with radiative intensity measurements and modelling, constrains the plasma temperature field, with IR imaging defining the spatial structure and radiative intensity matching setting the absolute temperature scale. Overall, the combined diagnostic–modelling framework demonstrates a feasible pathway for non-intrusive, spatially resolved temperature reconstruction in CO₂ plasmas relevant to electrified high-temperature industrial applications, where spectrally resolved diagnostics are often difficult to implement.

Novelty and significance statement: This work demonstrates a new approach for temperature reconstruction in CO₂-based thermal plasma jets by combining calibrated infrared imaging with total radiative intensity measurements and detailed spectral radiative transfer modelling. The method links camera counts, photon flux, and gas temperature through radiative transfer modelling, enabling non-intrusive, spatially resolved diagnostics of plasma-assisted heating. By combining the different measurement techniques, the possible temperature distributions within the plasma jet can be more narrowly constrained, improving agreement between modelled and measured radiation. The study provides new insight into radiative heat transfer mechanisms relevant to electrified, high-temperature industrial processes.

1. Introduction

Reducing greenhouse gas emissions from energy-intensive industries is essential to mitigate global warming. While many processes can be electrified, high-temperature sectors such as cement, lime, and iron-ore production still rely on fossil-fueled rotary kilns, where radiative heating from large flames leads to significant CO₂ emissions [1]. Thermal plasma heating offers a promising route toward electrification of such processes,

providing extremely high temperatures.

In this work, the possibility of substituting the burner in a cement rotary kiln with electrically powered plasma torches is investigated. CO₂ is inherently released during calcination and could with advantage be used as the plasma torch working gas, possibly creating a closed and radiatively efficient system [2]. However, such heat source transitions risk altering the bed heat treatment and product quality. Comprehensive experimental and modelling work is therefore required to ensure process

^{*} Corresponding author.

E-mail address: adriang@chalmers.se (A. Gunnarsson).

<https://doi.org/10.1016/j.proci.2026.106690>

Received 13 March 2026; Accepted 20 July 2026

Available online 27 October 2026

1540-7489/© 2026 The Authors. Published by Elsevier Inc. on behalf of The Combustion Institute. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

stability, although quantitative temperature diagnostics remain difficult due to high temperatures and the radiative and spectral characteristics of the plasma jet. CO₂-based plasma systems have been investigated for gasification and CO₂ dissociation [3–6], yet their radiative heat transfer characteristics and applicability as heat sources in industrial processes remain largely unexplored.

This study presents experimental work on a stand-alone CO₂ plasma jet at 50 kW_{el} in open air and combines thermal imaging and narrow-angle radiometry (NAR) with spectral radiative modelling using a statistical narrow band model (SNBM) to reconstruct temperature distributions along the plasma. Measured digital counts captured with an IR-camera are related to photon flux through radiative modelling, accounting for gas absorption, lens transmissivity, and detector sensitivity.

However, the radiative emission from a CO₂ plasma depends not only on temperature, but also on gas composition. To assess effects from CO₂ dissociation close to the plasma torch outlet and downstream entrainment of ambient air, a limited computational fluid dynamics (CFD) analysis is used to estimate the gas composition. The CFD results are not used to prescribe the temperature field, which is reconstructed from the combined IR-imaging and NAR measurements.

2. Experimental setup

Radiative heat transfer from a 50 kW_{el} stand-alone plasma jet using CO₂ as the working gas, operated in open-air conditions, was investigated. The plasma torch is a water-cooled, non-transferred arc thermal plasma. It was operated at a working gas flow of 14 Nm³/h, 1003 V and 50A with a thermal efficiency of about 83%.

Measurements of the radiative intensity were gathered using a narrow angle radiometer (NAR) with a 2 M thin film-based thermopile detector, spanning a waveband of 0.1–100 μm. The probes line of sight, at an approximate solid angle of 9.5×10^{-5} sr, was aligned with the axis of the plasma jet. The detector signal was recorded using a NI USB-621x DAQ, at a sampling rate of 10 Hz, and the NAR signal was calibrated to a blackbody LAND R1500T furnace before and after the measurements. To map the axial radiative intensity distribution, the optical axis of the NAR was shifted along the jet axis.

Thermal imaging was performed using a 7.5–14 μm infrared (IR) FLIR A655sc camera, with spectral response in 6.8–17 μm. It has a microbolometer detector and a germanium lens. The camera was positioned at a 90° viewing angle relative to the jet axis. Images were recorded at 50 Hz, 640 × 480 pixels.

Fig. 1 shows a schematic of the experimental setup, including the torch, the visible flame envelope, IR camera orientation and NAR placement. Additional details on the diagnostic setup and calibration procedures are provided in the Supplementary Material.

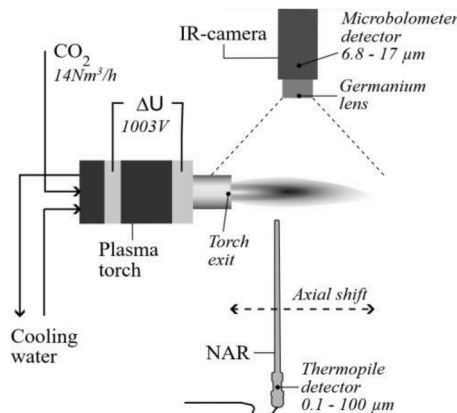


Fig. 1. Schematic of the experimental setup.

3. Modelling

The present methodology reconstructs spatially resolved temperature fields of a CO₂ plasma jet by combining radiative diagnostics with complementary spectral sensitivities. Since spectral emission depends on both temperature and gas composition, spectrally integrated measurements lead to a non-unique inverse problem; the approach is therefore formulated as a constrained reconstruction, where infrared imaging provides the relative spatial temperature distribution and the absolute temperature scale is obtained by matching measured radiative intensity using forward radiative transfer modelling. In this framework, infrared imaging provides spatial information, while the nonlinear relationship between radiation and temperature is handled through forward radiative transfer modelling. Supporting CFD is used only to interpret composition-driven optical-thickness effects and does not prescribe the temperature field. A step-by-step description of the data processing and reconstruction procedure is provided in the Supplementary Material.

3.1. Radiative intensity modelling

The radiative modelling reconstructs the CO₂ plasma jet temperature field by relating measured IR-camera counts and measured broadband radiative intensity (NAR) to the governing gas temperature and optical thickness. The infrared signal represents line-of-sight integrated radiation, and path-length effects are accounted for in the forward radiative transfer modelling rather than through direct inversion techniques such as Abel transformation.

The radiative intensity field is modelled using a discrete transfer method (DTM) along the plasma jet axis. The radiative transfer equation is solved using the Malkmus SNBM [7] with parameters of the mean line spacing, d_k , and the mean line-intensity to the typical line-spacing ratio, k_k , for CO₂ and CO from Rivère and Soufiani [8], using the CDSD-4000 database [9] for CO₂ absorption spectra, shown to be accurate up to 4000 K [10], and the HITEMP 2010 database [11] for CO. The spectrally averaged transmissivity of a narrow band k with a bandwidth $\Delta\nu$ of 25 cm⁻¹ is calculated for a gas (g) according to Eq. (1) where PS is the pressure-path-length and γ_g the mean line half-widths [7].

$$\bar{\tau}_{\nu_k,g} = \exp \left[-\frac{2\gamma_g}{d_k} \left(\sqrt{1 + \frac{Y_g P S k_k d_k}{\gamma_g}} - 1 \right) \right] \quad (1)$$

In the DTM, radiative intensity is calculated by tracing rays through the domain, assuming an axisymmetric and axially uniform gas temperature and gas concentration distribution. As each ray is traced, the spectral intensity at a given cell node depends on emission from upstream cells and wall radiation. It is obtained by summing the transmissivity differences between adjacent cell faces, multiplied by the local spectral blackbody intensity [12].

A radial grid of 60 computational cells is used. Grid refinement tests show that further refinement changes the integrated radiative intensity and predicted infrared photon flux by less than a few percent, indicating that numerical discretization does not limit the reconstruction accuracy.

Spectral gas transmissivities along the line-of-path of the NAR and IR-cameras detectors are determined for all measurement positions and the total intensity as well as the photon fluxes are determined within the spectral ranges of 0.1–100 μm and 6.8–17 μm.

To accurately account for the intensity reaching the detector of the IR-camera, the spectral transmissivity of the lens and the spectral sensitivity of the detector must be considered, illustrated in Fig. 2. The figure also presents the respective spectral transmissivity of pure CO₂ and pure CO gas layer at 2000 K with a 20 mm path length. The spectral characteristics show an overlap between the camera's detection range and the CO₂ absorption band, while there is no overlap with the CO absorption band, indicating that the IR camera is sensitive to CO₂ but not CO gas radiation.

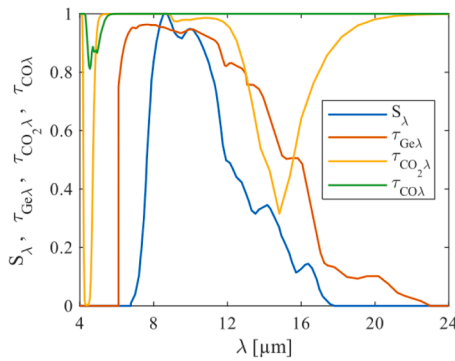


Fig. 2. Spectral properties of detector sensitivity (S_λ), lens transmissivity ($\tau_{Ge\lambda}$) and the respective gas transmissivity of a 20 mm CO_2 ($\tau_{\text{CO}_2\lambda}$) and CO ($\tau_{\text{CO}\lambda}$) gas at 2000 K.

While Fig. 2 shows representative spectra at 2000 K, significantly higher temperatures are expected in thermal plasma. At fixed gas composition, increasing temperature redistributes absorption among a larger number of vibrational–rotational transitions, which can lead to increased band-averaged transmissivity, while the dominant CO_2 absorption bands continue to overlap with the infrared camera spectral sensitivity range.

The predictive deviation of the model with respect to the radiation incident on the IR camera is quantified by comparing measured digital counts and model-predicted counts. Since the IR camera records only digital counts, C_{IR} , while the radiative transfer model predicts spectral photon flux, a conversion between the two is required. Establishing this relationship allows direct comparison between measured and modelled band-limited radiation and is essential for using IR-count distributions to constrain the temperature reconstruction. Without this mapping, the IR images could only be used qualitatively. Hence, the modelled spectral gas intensity is converted to equivalent units using spectral photon fluxes. Assuming a linear detector response, the background measurement provides a reference linking the background photon flux ($\phi_{qv,b}$) to the recorded background counts (C_b) after correction for the camera dark counts (C_{dark}). The total predicted incident radiation, i.e. gas emission and background contribution, expressed as spectral photon flux $\phi_{qv,g}$, can therefore be converted to equivalent camera counts using the ratio between the total and background photon fluxes, according to Eq. (2).

$$C_{IR} = \frac{\int_{IR} \phi_{qv,g} d\nu}{\int_{IR} \phi_{qv,b} d\nu} (C_b - C_{dark}) + C_{dark} \quad (2)$$

In practice, Eq. (2) is applied by integrating the model-predicted spectral photon flux over the camera's spectral response and converting it to equivalent digital counts using the background reference for direct comparison with measurements. Although the infrared signal varies nonlinearly with temperature due to radiative emission and absorption, it may preserve the spatial ordering of the temperature field when the gas composition is approximately constant, whereas variations in local CO_2 and CO concentrations can alter the infrared signal independently of temperature.

3.2. Assessment of CO_2 dissociation and dilution effects using CFD

To assess the plausibility and spatial extent of CO_2 dissociation and subsequent dilution in the near field of the plasma jet, a limited computational fluid dynamics (CFD) study was performed as a supporting analysis. The CFD is used to characterize thermo-chemical trends (composition and mixing) under the estimated operating conditions; it does not prescribe the temperature field used in the radiative reconstruction as presented above.

CFD simulations were performed using ANSYS Fluent to resolve the three-dimensional thermo-chemical flow field of the non-transferred CO_2 plasma jet under atmospheric conditions. The simulations were conducted under steady-state assumptions in a fully three-dimensional computational domain without the assumption of any geometric symmetry.

The numerical procedure was divided into two sequential stages. In the first stage, a simplified torch-exit/electrode region was modelled with a uniform volumetric heat source representing the effective thermal power delivered to the working gas (electrical input minus cooling losses), while CO_2 was supplied at the experimental mass flow rate. The resulting outlet temperature and species composition formed the inlet conditions for the second stage, in which the jet discharged into an open, ambient-pressure air domain that permitted entrainment.

Species transport was solved for CO_2 , CO, and O_2 , with chemical effects represented using a relaxation-to-chemical-equilibrium approach for the reaction $\text{CO}_2 \rightleftharpoons \text{CO} + \frac{1}{2}\text{O}_2$, allowing the local gas composition to evolve toward thermodynamic equilibrium under high-temperature conditions, thereby accounting for CO_2 dissociation and recombination processes within the plasma core and mixing region. This reduced chemical formulation captures the dominant dissociation trends affecting gas composition and infrared optical thickness under the present conditions. Minor species such as atomic oxygen are not explicitly resolved; their contribution to the infrared radiation within the camera spectral range is expected to be negligible compared to CO_2 . This simplification may affect detailed radiative properties at the highest temperatures but is considered sufficient for the present phenomenological assessment of optical-thickness effects in both broadband and band-limited radiative modelling. Thermophysical properties were treated using the ideal gas law.

Turbulence was modeled using the k- ω SST (Shear Stress Transport) model to resolve the strong shear gradients and mixing layers characteristic of high-velocity reacting jets. Radiative heat transfer within the CFD domain was accounted for using the Discrete Ordinates (DO) radiation model in combination with a Weighted Sum of Gray Gases Model (WSGGM) with high-temperature parameters by Ehlme et al. [13], thereby incorporating gas radiation effects.

Steady-state convergence was assessed through verification of global mass and energy balance closure.

4. Results and discussion

The 50-kW_{el} CO_2 plasma torch was operated under stable conditions for a total of 75 min during the measurements. Fig. 3a shows a photo of the plasma torch and the plasma jet within the visible spectra. The plasma jet exhibited a bright blue, slightly conical shape with a distinct core region and faint emission in the surrounding flow. The visible length of the jet was approximately 200 mm and the jet appeared steady in both length and radial size during the time of measurements.

Fig. 3b presents the spatial distribution of recorded counts within the camera's spectral range of 6.8–17 μm for three sequential images with a 5 s interval. The recorded counts peak near the torch exit and gradually decrease downstream, and the jet appears noticeably longer in the IR images than in the corresponding VIS photograph, reflecting emission from cooler downstream regions that remain radiatively active in the infrared. Evaluation of the complete IR image sequence acquired at 50 Hz revealed no significant temporal fluctuations in the recorded counts. The frames at 0, 5, and 10 s are shown as representative samples, demonstrating that the plasma jet remains stable in both shape and counts, with only negligible variation over time. Since the IR jet appearance was found to be temporally stable, the reconstruction uses the radial count distribution from a single representative frame for each axial position. This avoids unnecessary averaging while ensuring that the extracted profiles are not influenced by temporal fluctuations. The measured counts form the basis for the subsequent temperature reconstruction and comparison with the radiative transfer model.

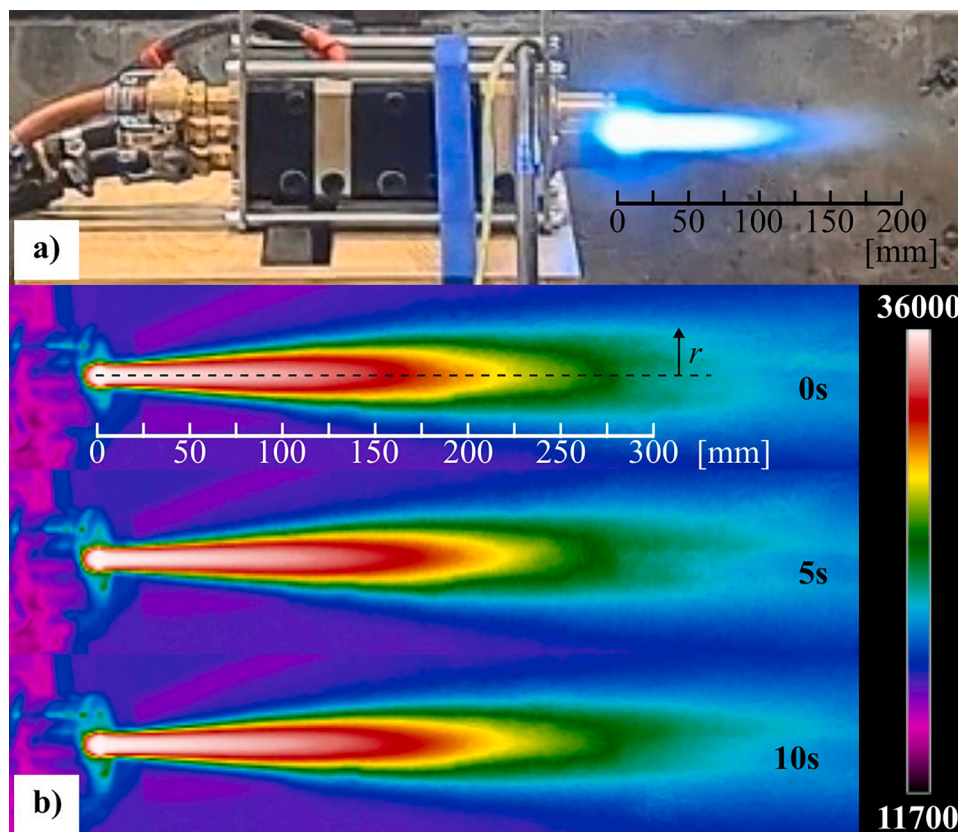


Fig. 3. Photos of the 50 kW_{el} CO₂ plasma torch operated in open air, shown in (a) VIS and (b) IR spectral ranges. Axial distances from the generator outlet are indicated, together with the plasma jet centerline and the radial direction (r).

The radiative intensity was measured using the NAR along the plasma jet axis in 20 mm increments, starting from 20 mm downstream of the torch exit, with an additional position 5 mm downstream of the torch exit, with a total of eight axial positions.

4.1. Radiative intensity modelling

The temperature field is reconstructed by combining normalized infrared count distributions with a single absolute calibration provided by the broadband NAR measurement.

The SNB model was used to model the total intensity reaching the NAR probe and IR-camera detector. The temperature and jet-radius distributions were parameterized based on the infrared imaging counts, which peak along the jet axis and decrease toward the jet radial boundary. At each axial measurement position of the NAR, the IR counts were evaluated along the flame radius and normalized globally by the maximum value at the 20 mm downstream measurement position to obtain relative temperature distribution shape. Normalization was performed at this axial position rather than at the peak value at 5 mm, where strong CO₂ dissociation and steep composition gradients led to poor agreement with the measured radiative intensity values. At 20 mm, dissociation effects are less pronounced, and the gas composition is more uniform, providing a more reliable reference point for the combined NAR–IR calibration. Here, at the 20 mm position, the peak temperature was iteratively determined to 3039 K by fitting the modelled and measured (NAR) total radiative intensity values. The temperature profiles are parameterized using the normalized IR-count distribution as a spatial weighting, which defines the relative spatial structure of the temperature field, while the absolute temperature scale is determined independently by radiative intensity matching.

The IR-count distribution was further used to set the radius of the plasma jet at each position. A gas volume with an elevated temperature,

in comparison to the surroundings, was assumed to solely contain CO₂ gas. A surrounding gas layer consisting of ambient air is also included in the model at the radial boundary of the jet. The boundary of the modelled volume was set as cold, absorbing walls at 293 K with a surface emissivity of unity. That is, the background contribution is negligible and no reflections are considered.

Fig. 4 shows the resulting temperature profiles for the reconstructed temperature field of the plasma jet. The temperature peaks at the torch exit (5 mm, 3665 K) and the jet radius expands in the downstream direction. The radiative intensity was computed using a radial grid of 60 computational cells, whereas the temperature profiles based on IR images have an effective spatial resolution of approximately 1.4 mm. Thus, the modelling grid provides a finer discretization than the measurement

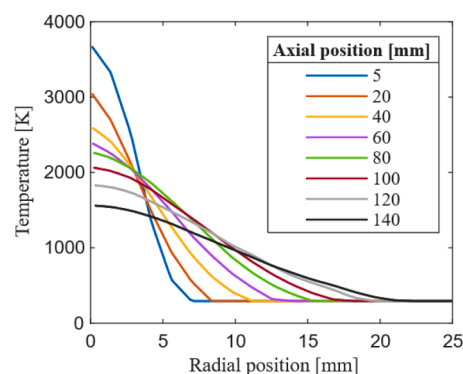


Fig. 4. Radial temperature profiles for all axial positions based on a normalized IR-counts distribution. The apparent step-like behavior reflects the discrete radial representation of the reconstructed temperature field, with linear interpolation assumed between grid points.

resolution.

Fig. 5 shows the measured, I_{meas} , and modelled, I_{mod} , radiative intensities along the plasma jet axis at all NAR measurement positions. Again, modelled intensity at the 20 mm axial position was fitted to the measured value by varying the peak temperature. As can be observed, the radiative intensity is reduced along the axis of the jet, and the measured and modelled values compare well for additional positions 40 – 100 mm downstream of the torch exit with intensity deviations ranging from 4 – 14%. The largest intensity deviation is at the downstream position of 140 mm from the torch exit with a deviation of 52%. This is explained by the assumption of the gas volume considered to be solely CO_2 , causing a high absorption in the colder gas region at the plasma jet radial boundary. At the downstream positions (100 – 140 mm), transparent air is probably mixed with the CO_2 , causing a reduced absorption.

Fig. 5 also shows how the modelled photon fluxes to the IR-camera detector deviate from the measured value, expressed in terms of counts. Here, the spectral properties of the CO_2 gas, germanium lens and sensitivity of the detector (see Fig. 2) are accounted for. The large deviations can again be explained by the simplified gas concentration profile used in the model where neither CO_2 dissociation close to the plasma torch exit nor downstream air entrainment are accounted for. However, although the modelled and measured intensities remain in good agreement at the downstream positions 20 – 100 mm, the counts deviation is relatively large. This reflects that the NAR measurement is a broadband measurement (0.1 – 100 μm) while the IR-camera is sensitive to CO_2 -band optical-thickness effects within the 6.8 – 17 μm band, indicating a stronger sensitive effect from dilution and gas concentration effects.

To assess the influence of the spatial extent of optically participating CO_2 on the infrared photon-flux predictions, an alternative modelling case was evaluated in which the effective radiative CO_2 region was reduced. In this formulation, only the inner region of the jet, where CO_2 concentration and temperature remain high, was treated as radiatively active, while the outer, colder and more diluted gas was represented as non-participating. That is, the temperature profiles and CO_2 concentrations drop sharply to the ambient conditions. The reduction of the effective radiatively participating radius is not introduced as a numerical fitting parameter, but as a phenomenological representation of reduced optical thickness caused by CO_2 dissociation at high temperatures and dilution due to entrainment of ambient air. This interpretation is supported by the results showing that the broadband radiative intensity is well predicted, while the band-limited infrared counts are systematically overpredicted when assuming a radially extended, cold CO_2 layer. Consistent with this interpretation, reducing the effective radiative radius substantially decreases the predicted photon-flux deviation, as shown in Fig. 6, by limiting absorption from cold boundary layers that otherwise attenuate the band-limited infrared signal.

For the reduced radius case, the jet radius was decreased to limit

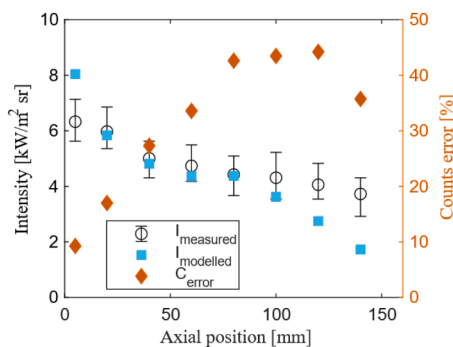


Fig. 5. Measured and modelled radiative intensities together with photon flux (counts) deviation to the IR detector.

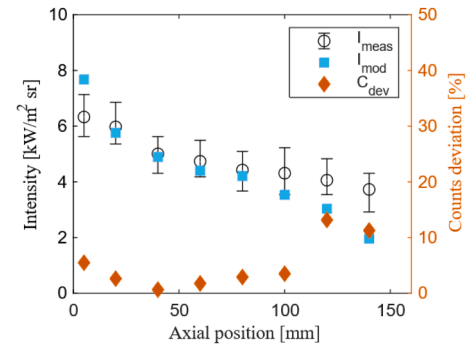


Fig. 6. Measured and modelled radiative intensities and IR-count deviation for the reduced effective jet radius.

absorption from the colder boundary layers and thereby reduce the IR-count deviation. The peak temperature at the 20 mm position was re-adjusted to 2594 K to maintain agreement between measured and modelled radiative intensities. This updated peak temperature was then used to set the absolute temperature scale for the reconstructed profiles while preserving the IR-derived spatial structure. The resulting temperature profiles for the reduced effective CO_2 region are shown in Fig. 7, where the peak temperature at 5 mm decreases by approximately 530 K to 3139 K.

The high temperatures near the torch exit (> 3000 K) indicate that partial CO_2 dissociation is likely within the core region. Such dissociation reduces the local CO_2 mole fraction and therefore the radiative participation of the gas, particularly within the infrared absorption bands relevant to the camera, see Fig. 2. Although CO and CO_2 possess overlapping emission features, changes in composition alter both emissivity and absorption coefficients and may further contribute to the observed deviations, especially close to the plasma outlet. Quantifying these effects is outside the scope of the present reconstruction but is addressed qualitatively using CFD analysis in the following section.

4.2. CO_2 dissociation and dilution effects

From the limited two-stage CFD-simulations of the plasma jet, the radial gas composition along the jet axis is estimated and shown for the axial positions 5 and 120 mm downstream of the plasma torch exit in Fig. 8. The resolved fields show that the CO_2 mole fraction decreases to approximately 60% at the 5 mm axial position downstream of the torch exit while the CO concentration reaches about 27% due to partial CO_2 dissociation at the peak temperatures. Further downstream, the CO_2 concentration does not return to unity but continues to decline due to entrainment of ambient air and mixing in the shear layer. At the 120 mm position, the CO_2 concentration is about 41% while the CO concentration is reduced to about 5%.

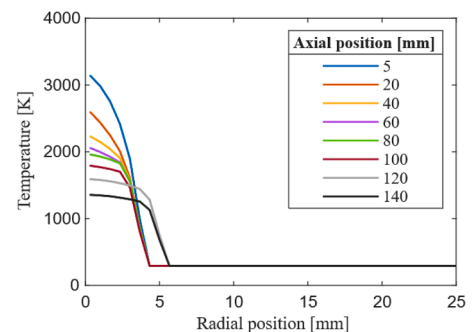


Fig. 7. Radial temperature profiles for all axial positions with a reduced jet radius. The apparent step-like behavior arises from the same discrete radial representation as in Fig. 4.

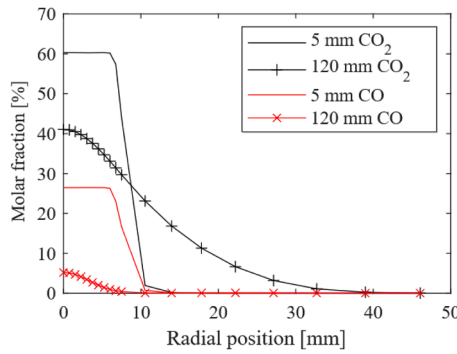


Fig. 8. Radial variation of CO₂ and CO at 5 mm and 120 mm from Plasma torch exit.

These results indicate that both dissociation and dilution reduce the local CO₂ concentration in the regions most relevant for infrared emission and absorption. The CFD-derived composition fields were therefore used only to assess the expected optical-thickness variations at selected axial positions and to support interpretation of the radiative discrepancies, while the temperature reconstruction remained based solely on the combined NAR and IR measurements.

Applying the CFD-predicted gas composition at the 20 mm position, the peak temperature used was again re-adjusted to match the measured radiative intensity. The fitted peak temperature at this position reaches 3336 K. The CFD gas concentrations are further used to analyze the results near the plasma torch exit at 5 mm and at the downstream position of 120 mm.

Fig. 9 shows a comparison of the modelled intensity and the IR-camera counts deviation, assuming pure CO₂ (in accordance with Fig. 5) or CFD gas concentrations, at the selected positions of 5, 20 and 120 mm. As can be seen, applying the temperature profile based on the normalized IR-counts together with the CFD gas concentrations reduces the discrepancy between measured and modelled radiative intensity at 5 mm. This behavior is consistent with dissociation reducing the optical thickness, indicating that dissociation effects are important at these high temperatures. However, the deviation in camera counts remains in the same range as observed for the pure CO₂ case.

At the downstream position of 120 mm position, substantial air entrainment into the jet is predicted by the CFD results. Here as well, the prediction of the radiative intensity is more in line with measurements, while the deviation in camera counts is significantly reduced from 44% to 9%. This suggests that discrepancies in the downstream field are primarily governed by the combined effects of air-driven dilution and the effective radiative participation of the CO₂ core.

The CFD simulations capture the dominant trends of CO₂ dissociation and downstream dilution affecting optical thickness. Minor species and electronically excited states are not explicitly resolved; their

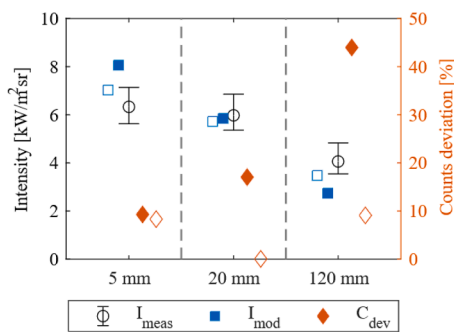


Fig. 9. Comparison of measured and modelled intensity and IR-count deviation using pure CO₂ (filled) and CFD-derived gas composition (open) at 5, 20 and 120 mm.

contribution to the infrared radiation considered here is expected to be negligible. CFD results are used to support the physical interpretation of radiative discrepancies and, where applicable, to provide gas-composition input for the radiative transfer calculations, but are not employed to prescribe the radial temperature field.

4.3. Sensitivity to peak temperature, CO₂ concentration and background counts

To assess robustness and to separate the effects from calibrated peak temperature (at 20 mm), gas composition, and background-reference effects in the counts mapping, a targeted sensitivity analysis was performed at the 5 mm (high dissociation) and 120 mm (high air entrainment) positions from the plasma torch outlet. The nominal case uses the gas composition based on the CFD findings, presented in Figs. 8 and 9, a single absolute temperature calibration at the 20 mm position to fit measured radiative intensity, presented in Fig. 9, and IR-counts based radial shapes at all axial positions. Sensitivities were then evaluated by shifting the calibrated peak temperature at 20 mm by $\pm 5\%$ (causing a change of all axial and radial temperatures), the molar fraction of CO₂ at each position by $\pm 10\%$, and the IR-camera background counts were changed by $\pm 10\%$ in the flux-to-counts mapping (see Eq. (2)).

Fig. 10 shows the result from the sensitivity analysis of the parameters examined for the two selected positions. Note that no sensitivity analysis is shown for the background counts for the modelled intensity to the NAR since it is independent on the IR-camera counts.

As can be observed at both positions, the modelled intensity is more responsive than the counts deviation for the shift in calibration peak temperature. This reflects the integral nature of the NAR measurement, which aggregates emission over the full spectrum and is governed primarily by the absolute temperature and participating volume.

At the 5 mm position, the modelled intensity is more sensitive to the shift in CO₂ concentration, than at the 120 mm position. This is partly because of the gas concentration already being lower at the downstream position, partly because of the lower temperatures at the 120 mm position. That is, in the upstream position, the gas emission is high and hence it is more sensitive to a shift in gas concentration. However, the counts deviation exhibits similar sensitivity to CO₂ concentration at 5 mm and 120 mm. Though, the IR-camera only responds to changes within the 6.8–17 μm band.

The sensitivity to the background level is largest of all counts deviation factors: a $\pm 10\%$ change in the background counts leads to counts-deviation variations on the order of 5–25%, underscoring the importance of a stable background reference and correct spectral weighting in the flux-to-counts conversion.

Taken together, these results confirm that the single peak temperature calibration at 20 mm is appropriate for setting the temperature scale of the reconstruction, that gas composition is essential to control band-limited deviations, and that the background counts reference is a leading uncertainty for the counts comparison. The complementary

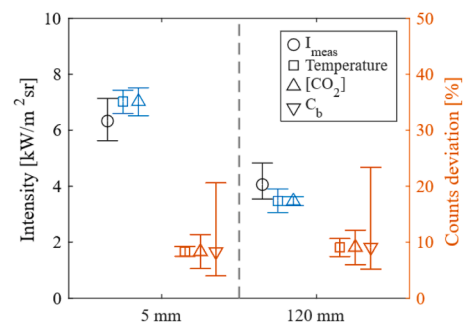


Fig. 10. Sensitivity analysis of modelled radiative intensity (blue) and counts deviation (orange) varying calibrated peak temperature at 20 mm $\pm 5\%$, CO₂ concentration $\pm 10\%$ and background counts (C_b) $\pm 10\%$.

sensitivities of NAR and IR measurements reduce the solution space of the inverse problem, constraining both the absolute temperature scale and the spatial structure.

5. Conclusions

This study examines how spatial count distributions obtained from infrared thermal imaging can be used in combination with total radiative intensity measurements to reconstruct temperature fields of a thermal plasma jet. By combining experimental measurements with detailed radiative transfer modelling, the total and band-limited radiative intensities were compared with measured data, enabling an assessment of the relation between detected counts, photon flux, and temperature.

The analysis shows that assuming a radially extended radiating region with a gradual temperature decay leads to systematic over-prediction of IR photon fluxes, despite good agreement with broadband NAR intensities. Introducing a sharper radial temperature drop, that is by effectively reducing the radiatively active CO₂ core, significantly improves the match with measured counts while preserving agreement with the NAR intensity measurement. This highlights the strong sensitivity of IR-based diagnostics to local optical thickness, especially within the 6.8–17 μm band where CO₂ absorption is dominant (in comparison to CO absorption).

CFD-based estimates of gas composition further indicate that both CO₂ dissociation near the torch outlet and entrainment-driven dilution downstream reduce the participating CO₂ fraction, thereby lowering the effective optical thickness. Incorporating these effects improves agreement between measured and modelled intensities at positions close to the plasma jet outlet as well as further downstream.

These findings highlight the potential of calibrated IR imaging, supported by spectral modelling, as a non-intrusive tool for physically constrained temperature reconstruction in plasma-assisted systems. The combined diagnostic–modelling approach enables spatially resolved temperature fields in high-temperature CO₂ plasmas, with broadband (NAR) and band-limited (IR) measurements providing complementary constraints on the inverse problem. While improved characterization of gas composition, background radiation, and the radiatively participating volume would further enhance accuracy, the present results show that reliable temperature distributions can be achieved for electrified high-temperature industrial applications.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Microsoft Copilot in order to assist with wording and clarity. The authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Adrian Gunnarsson: Writing – original draft, Visualization,

Methodology, Investigation, Data curation, Conceptualization. **Saumitra Mishra:** Writing – review & editing, Methodology, Data curation. **Ibrahim Qasim:** Writing – review & editing, Investigation, Data curation. **Klas Andersson:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This project has received funding from the Swedish Energy Agency under grant agreement No P2021-00015.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.proci.2026.106690](https://doi.org/10.1016/j.proci.2026.106690).

References

- [1] A. Gunnarsson, K. Andersson, B.R. Adams, C. Fredriksson, Full-scale 3D-modelling of the radiative heat transfer in rotary kilns with a present bed material, *Int. J. Heat Mass Transf.* 147 (2020) 118924.
- [2] A. Fakt, A. Gunnarsson, K. Andersson, F. Normann, B. Wilhelmsson, Evaluating heat transfer conditions in a plasma-heated rotary kiln for cement production, *Ind. Eng. Chem. Res.* 64 (2025) 8329–8338.
- [3] R. Mallick, P. Vairakannu, Experimental studies on CO₂-thermal plasma gasification of refused derived fuel feedstock for clean syngas production, *Energy* 288 (2024) 129766.
- [4] P. Amarnath, N. Nandy, B. Indumathy, S. Yugeswaran, Study on CO₂ based thermal plasma torch and its effective utilization for material processing in atmospheric pressure, *J. CO₂ Util.* 66 (2022) 102290.
- [5] M. Wang, Y. Yu, B. Su, W. Zhang, Q. Yang, Efficient syngas production from medical waste by CO₂ thermal plasma gasification, *Chinese J. Chem. Eng.* 83 (2025) 88–97.
- [6] J. Li, X. Zhang, J. Shen, T. Ran, P. Chen, Y. Yin, Dissociation of CO₂ by thermal plasma with contracting nozzle quenching, *J. CO₂ Util.* 21 (2017) 72–76.
- [7] W. Malkmus, Random Lorentz band model with exponential-tailed S-1 line-intensity distribution function, *J. Opt. Soc. Am.* 57 (1967) 323.
- [8] P. Rivière, S. Soufiani, Updated band model parameters for H₂O, CO₂, CH₄ and CO radiation at high temperature, *Int. J. Heat Mass Transf.* 55 (2012) 3349–3358.
- [9] S.A. Tashkun, V.I. Perevalov, L.H. Coudert, CDSD-4000: high-resolution, high-temperature carbon dioxide spectroscopic databank, *J. Quant. Spectrosc. Radiat. Transf.* 112 (2011) 1403–1410.
- [10] S. Depraz, M.-Y. Perrin, P. Rivière, A. Soufiani, Infrared emission spectroscopy of CO₂ at high temperature. Part II: experimental results and comparisons with spectroscopic databases, *J. Quant. Spectrosc. Radiat. Transf.* 113 (2012) 14–25.
- [11] L.S. Rothman, I.E. Gordon, R.J. Barber, H. Dothe, R.R. Gamache, A. Goldman, V. I. Perevalov, S.A. Tashkun, J. Tennyson, Hitemp, the high-temperature molecular spectroscopic database, *J. Quant. Spectrosc. Radiat. Transf.* 111 (2010) 2139–2150.
- [12] R. Johansson, B. Leckner, K. Andersson, F. Johnsson, Influence of particle and gas radiation in oxy-fuel combustion, *Int. J. Heat Mass Transf.* 65 (2013) 143–152.
- [13] E. Ehlme, A. Gunnarsson, F. Normann, K. Andersson, Updated weighted-sum-of-grey-gases model parameters for a wide range of water and carbon dioxide concentrations and temperatures up to 5000 K, *ACS Omega* 10 (2025) 2978–2985.