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# Model Development for the Heat Transfer of an Impinging Partially Premixed Acetylene/Air Flame to a Flat Target

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***Abstract*** – A CFD model for the assessment of the heat transfer efficiency between a partially premixed acetylene/compressed air flame jet and a flat target surface is developed. Different turbulence models are evaluated, and the impact of radiation is quantified. The results are verified using previously published experimental data. While different models based on the turbulent kinetic energy (k) and its dissipation rate (ε) seem not applicable due to a significant underprediction of the heat transfer efficiency, the SST k-ω model and the stress-ω RSM model provide better predictions. Radiation is deemed insignificant for the magnitude of the heat transferred within the system.

***Keywords*: Heat transfer, flame jet impingement, premixed acetylene/air combustion, flame heating

## Notations

| | | | |
|---|---|---|---|
| $D$ | Torch diameter | $HoC$ | Heat of Combustion, net caloric value |
| $\varepsilon$ | Dissipation rate of k | $k$ | Turbulent kinetic energy |
| $\eta$ | Efficiency | $y^+$ | Dimensionless wall distance |
| $H$ | Distance torch/target | $\omega$ | Specific dissipation rate of k |

## 1. Introduction

Industrial flame heating is vital to modern manufacturing processes with applications from hardening to flame straightening. Heat transfer (HT) occurs from the flame to the target and is commonly described by the flame jet impingement model (figure 1).

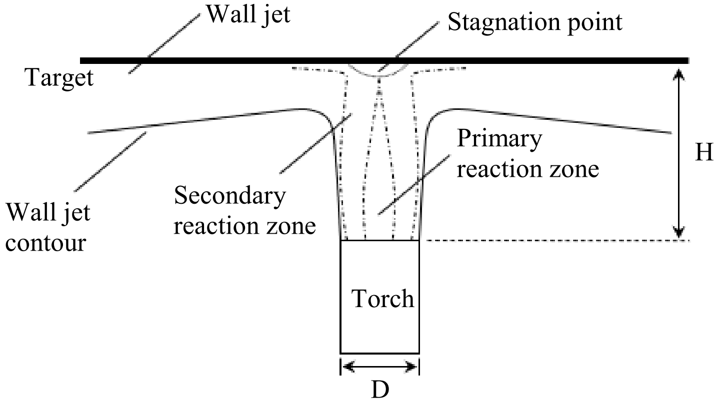


Figure 1: Hydrodynamic principles of flame jet impingement, HT occurs at the stagnation point and in the wall jet region.

A wide range of studies and reviews on the experimental assessment of flame jet impingement exist [1], [2], but numerical approaches have gradually become more important. The available body of literature contains documentations on models of varying focus using different methods to model the combustion process within the flow and the HT between the flame and the target. Many researchers use or assume laminar flow in their investigations [3], [4]. Application-related investigations include different RANS turbulence models for the description of the practically more relevant turbulent flames [5], [6]. With increasing capabilities of relevant algorithms and hardware power, methods like LES [7] or DNS [8] have become more feasible. However, for optimization workflows involving many parameters (fuel gas and oxidizer stream configurations, burner geometry, type of impingement target, etc.), it is still relevant to manage the computational efforts. Especially the interaction and simultaneous calculation of flow, turbulence, reaction, and radiation imposes challenges on the modelling approach. For flow and turbulence, the available fundamental investigations for isothermal jet impingement systems [9], [10] are significantly abundant. For the reaction, several combustion models are available in commercially available CFD codes [11]. In industry, reaction-rate dependent approaches such as the Eddy-Dissipation-Model and -Concept (EDx) are relevant, yet reduced order flamelet-based models provide a good combination between computational time and accuracy.

The main parameter of interest for a flame jet impingement system is the global HT efficiency. It is defined as the proportion of chemically stored heat of combustion (HoC, here the net caloric value) transferred into the target [12]. The setup of a computational fluid dynamics (CFD) model for the assessment of the HT is described. An initial experimental validation [12] for the investigated partially premixed acetylene/air flame is included to confirm the suitability of the model for the intended purposes such as torch design and optimization.

## 2. Methods

The model is implemented and solved within ANSYS' Fluent 23R2.

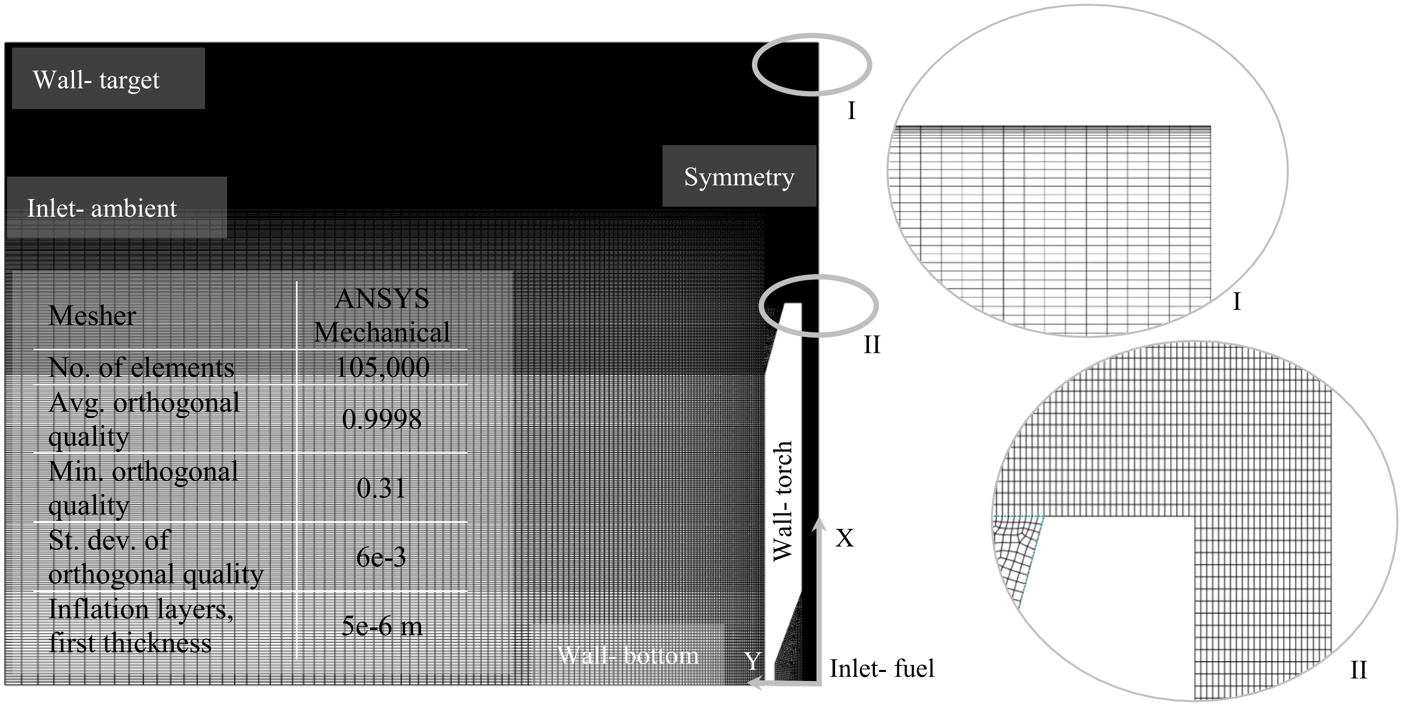
For flame jet impingement systems, the non-adiabatic Flamelet-Generated-Manifold (FGM) [11] is considered useful since local quenching or extinction within the stagnation point or wall jet region (especially in the boundary layer) must be assumed [7], [13]. In this study, GRIMECH 3.0 is taken as the underlying reaction mechanism [14]. For reduced-order turbulent combustion models such as the FGM, the turbulent flame speed is used to provide closure for the turbulence-chemistry interaction (TCI) [11]. Here, based on the laminar flame speed Zimont's approach to calculate the turbulent flame speed is used [11].

As the turbulence model has multiple and significant effects (TCI, jet spreading, boundary layer development and heat transfer), multiple models are evaluated (standard k-ε, RNG k-ε, realizable k-ε, SST k-ω with low-Re correction, stress-ω Reynolds-Stress model) [11]. All ε-based models are implemented using the "Enhanced wall treatment" [11].

Radiation is often considered negligible for impingement systems at ambient conditions but important for enclosed systems [13], [15]. The impact of radiation is evaluated comparing the P-1 and the Discrete Ordinates (DO) approach based on the weighted-sum-of-grey-gases model (WSGGM) [11].

### 2.1. Domain and mesh

Assuming 2D-axisymmetry, the domain (figure 2) has a radius equal to the hydraulic radius of the heat-exchanger (200 x 200 mm) used for the validation experiments [12]. Part of the internal torch geometry is modelled to capture turbulence effects within the torch. The distance between the torch and the target is variable and ranges between the normalized distances H/D = 4 and H/D = 12. The mesh (figure 2) includes inflation layers used to evaluate the accomplished resolution of the boundary layer in the stagnation point and the wall jet region. For the model convergence study the configuration of H/D = 8 is taken into consideration and the stress-ω Reynolds-Stress model (RSM) turbulence model is used. The selected mesh settings are fit to lead to proper convergence with respect to the relevant evaluation parameters and all $y^+$ values are well below 1.



| Mesher | ANSYS Mechanical |
|---|---|
| No. of elements | 105,000 |
| Avg. orthogonal quality | 0.9998 |
| Min. orthogonal quality | 0.31 |
| St. dev. of orthogonal quality | 6e-3 |
| Inflation layers, first thickness | 5e-6 m |

Figure 2: Domain, boundary conditions, global and local mesh details, and quality metrics for H/D = 8.

### 2.2. Boundary conditions

The specifications of the relevant boundary conditions (BC, table 1) selected for the model are listed below. BC “symmetry” assumes a 2D-axisymmetric configuration, the wall BC “wall- nozzle” and “wall- bottom” are adiabatic, smooth walls.

Table 1: Selected specifications for the boundary conditions as specified in figure 2.

*Inlet- fuel*
- Mass flow rate: 0.0003116 kg/s
- Turbulent intensity: 5 %
- Hydraulic diameter: 0.0117
- Temperature: 293.15 K
- Mean mixture fraction: 0.1467

*Inlet- ambient*
- Gauge pressure: 0 Pa
- Turbulent intensity: 5 %
- Turbulent viscosity ratio: 10
- Temperature: 293.15 K
- Mean mixture fraction: 0
- Emissivity: 1

*Wall- target,* copper
- External:
  - Smooth wall
  - Emissivity: 0.76 [16]
- Internal HT model [12]:
  - Heat transfer coefficient: 29 kW/m$^2$ K
  - Free Stream Temperature: 323 K
  - Wall Thickness: 0.002 m

The model is solved employing a pressure based coupled algorithm and second-order spatial discretization [11]. Models with multiple physics models often require a specific strategy to achieve convergence. For the RSM, an initially converged standard k-ε solution serves as a good domain initialization. Radiation is best included by freezing the flow field and running only the radiation equation (first P-1, then DO) for a few hundred iterations.

### 2.4. Experimental validation

Using previously published experimental data for the HT from an impinging jet flame into a water-cooled calorimeter [12], the quality of the numerical results is evaluated.

Table 2 contains the extracted flow configuration based on the Reynolds-number and the corresponding volume flow to calculate the mean mixture fraction at the BC “inlet- fuel” using the definition from the ASNYS Fluent theory guide [11].

Table 2: Acetylene/air ($C_2H_2$/Air) flow rate and associated Reynolds number for the fuel/air mixture at the torch outlet.

| *Reynolds number* | *Flow rate $C_2H_2$ [Nl/min]* | *Flow rate Air [Nl/min]* |
|---|---|---|
| 5250 | 2.33 | 14.7 |

## 3. Results and discussion

The following section presents the results of the numerical analysis investigating the impact of the turbulence model on the global HT into the target. Additionally, the impact of radiation on the HT mechanism is evaluated and a discussion based on a comparison between experimental and numerical results is included.

### 3.1. Turbulence models

All 2-equation models based on the turbulent kinetic energy (k) and its dissipation rate (ε) predict a much shorter primary reaction zone with its tip located closer to the torch than the SST k-ω model (figure 3). Figure 3 and figure 4 also indicate a significantly higher spreading rate of the flame and the wall jet using ε-based models: Figure 3 shows how hot flue gases are diverted from the reaction zone towards the ambient air while figure 4 depicts the significantly different magnitudes of turbulent intensity at the centerline of the domain.

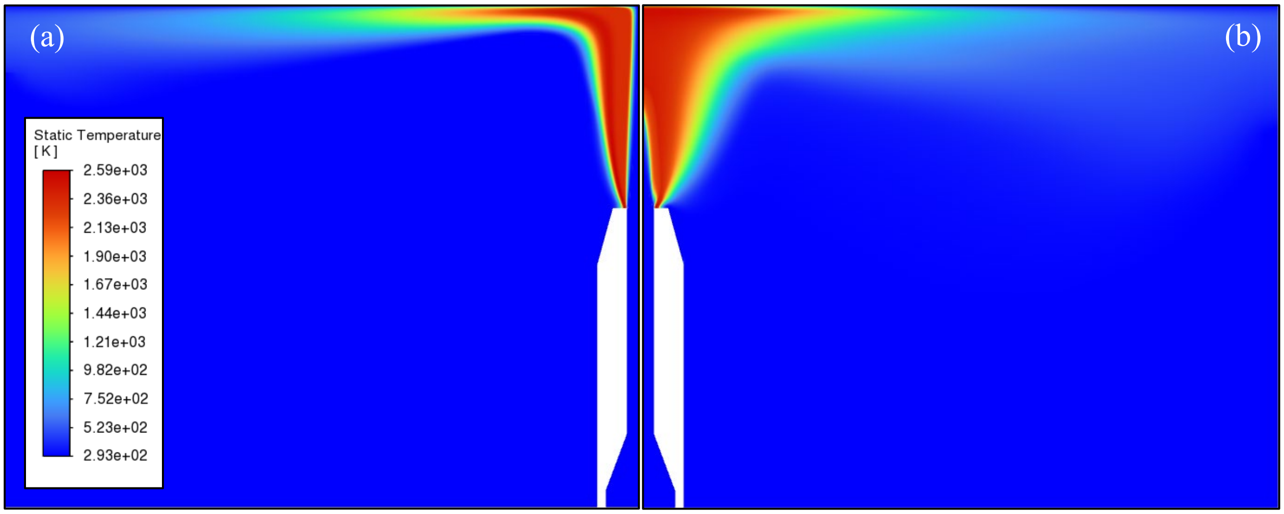


Figure 3: Temperature distribution for H/D = 8 and primary reaction zone for models (a) SST k-ω and (b) realizable k-ε.

Flame jet impingement systems at ambient conditions reach their highest efficiency for configurations, where the target is located slightly above the primary reaction zone [2], [12]. The prediction of a faster reaction, high heat release rates close to the torch and the resulting shorter primary reaction zone may result in a faulty estimation of the HT efficiency. Considering the global HT efficiency, figure 5 visualizes a continuously negative gradient for all ε- and ω-based 2-equation models as suggested by empirical correlations for isothermal gas jets on flat surfaces [17]. However, as described by Hargrave et al. [2], flame jets show an efficiency drop for low H/D values (figure 5): Based on the considered configurations, only the 5-equation RSM can predict the positive gradient before the ideal distance with the peak efficiency is reached. While 2-equation models assume an isotropic turbulence field, the RSM can to some degree account for anisotropic effects which may influence the heat transfer characteristics. As the target- parallel turbulent scales near or within the boundary layer of the wall jet or stagnation point may significantly differ from the scales normal to it, the RMS and the directional evaluation of turbulence effects seems relevant.

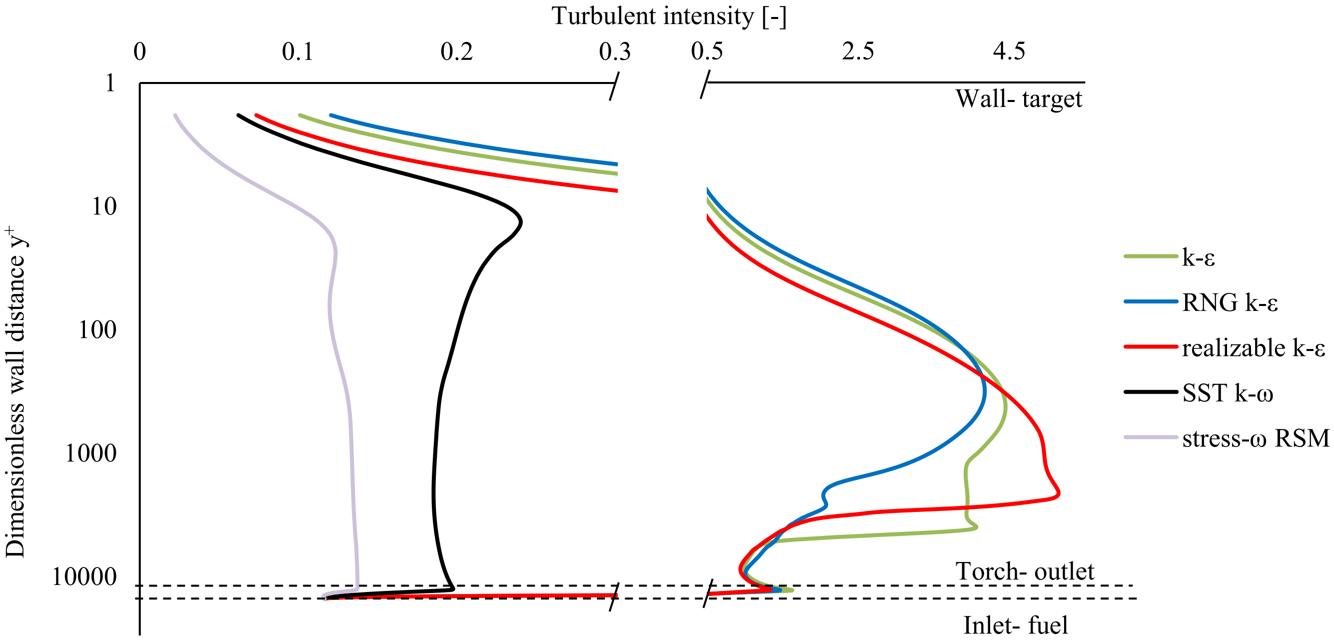


Figure 4: Turbulence intensity for all evaluated turbulence models along the centerline indicating a significantly higher turbulence generation for the k-ε models.

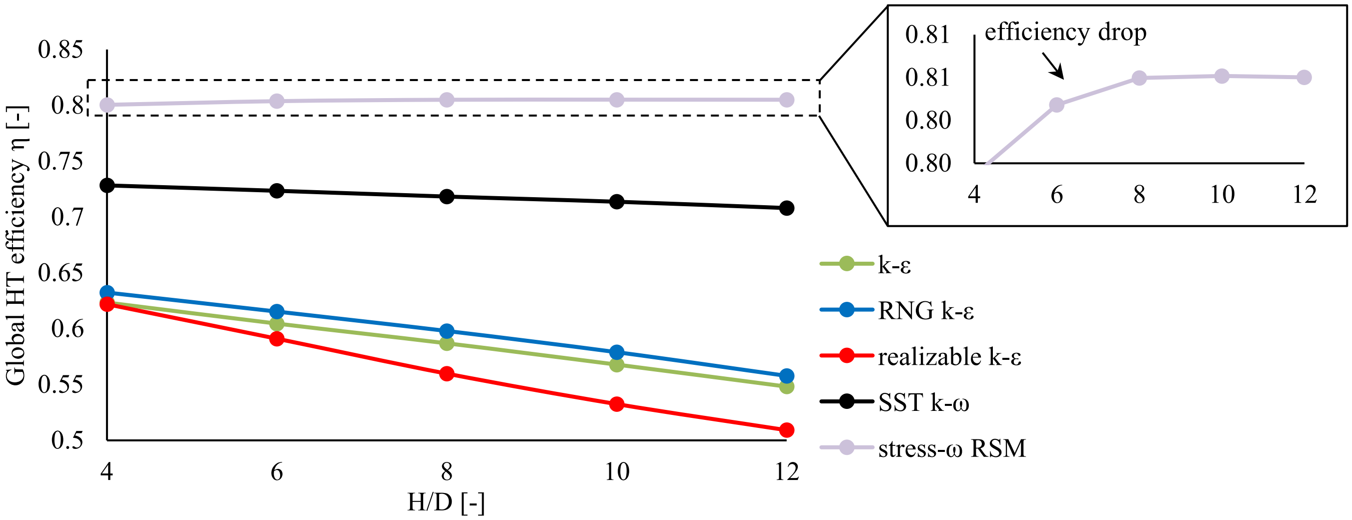


Figure 5: Flame jet impingement heat transfer efficiency for the investigated turbulence models and normalized distances H/D.

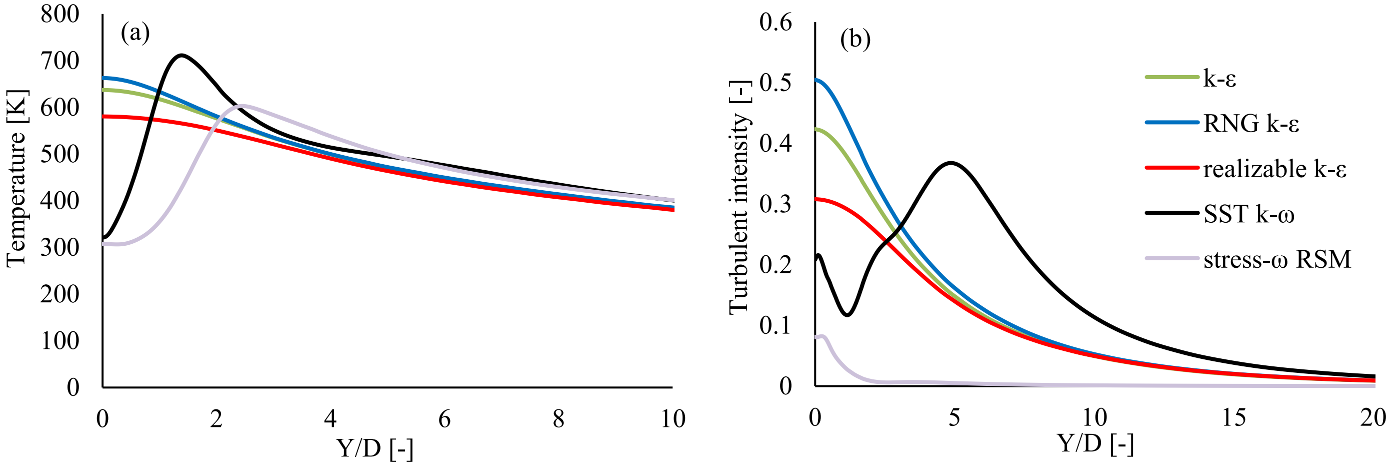


Figure 6: Temperature distribution (a) and turbulent intensity (b) along the BC wall- target at H/D = 7.99 ($y^+ \approx 1$).

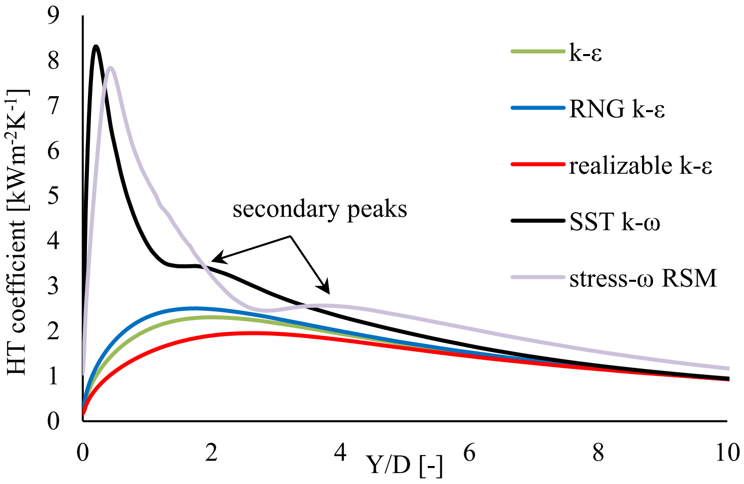


Figure 7: HT coefficient at H/D = 7.99 ($y^+ \approx 1$) incl. secondary peaks.

Both ω-based models can predict the secondary peak in the heat transfer coefficient and Nusselt number as previously described by experimental and numerical studies [18], [19]. The 5-equation RSM model results in the highest HT efficiency (figure 5), yet an inconsistency that requires further analyses remains:

1. Figure 6 (a) indicates clearly, that the RSM efficiency cannot be explained just by high peak temperatures in the proximity of the target as the RSM derives lower peak temperatures compared to the SST k-ω, k-ε and RNG k-ε models.
2. Figure 6 (b) suggests, that a low level of turbulent intensity close to the target is responsible for a high HT efficiency. However, the comparably high level of turbulent intensity for the SST k-ω model contradicts this conclusion.

### 3.2. Experimental validation

The CFD results are compared to previously published experimental data (figure 8, [12]). All ε-based models significantly underpredict the global HT efficiency. This is likely caused by the underprediction of the primary reaction zone as the experimental efficiency curve reaches its peak for H/D = 8, where the target is located just above the primary reaction zone [12]. The SST k-ω model results in a quantitively close match for the experimentally investigated flame of Re = 5250 despite the assumption of an ideally smooth wall- target BC. The RSM seemingly captures the efficiency drop for low H/D values as visualized and described in figure 5. For the significant underprediction of the effect in combination with an overprediction of the global HT efficiency, the suitability of the RSM requires further analyses.

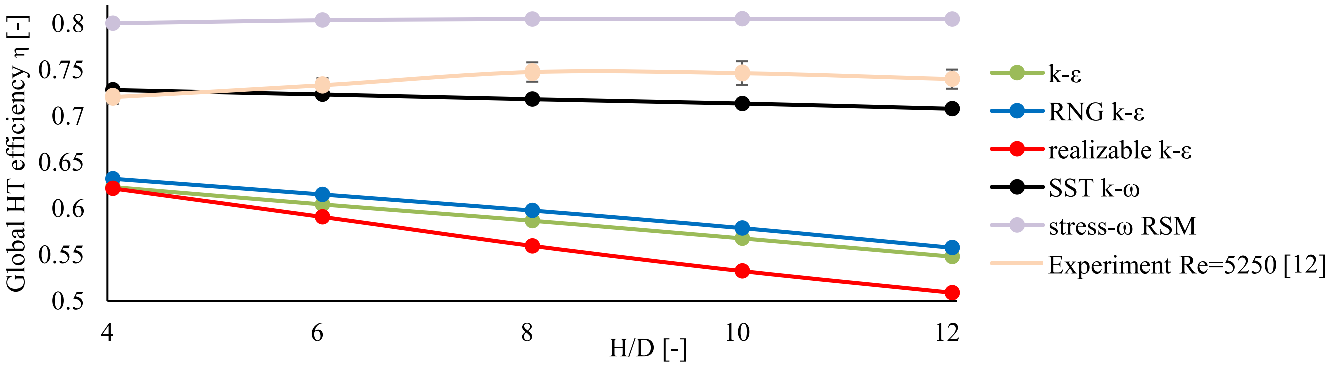


Figure 8: Flame jet impingement heat transfer efficiency for different turbulence models and normalized distances H/D.

### 3.3. Radiation impact

Assuming a twofold heat transfer mechanism (convection and radiation), both physical effects are taken into consideration using the P-1 and the DO models. For the DO approach, an independence study for angular discretization and pixelation was performed. Figure 9 shows the impact of different radiation models on the HT using the SST k-ω model as a baseline. Even though additional heat flux (HF) is created due to radiation, the radiative effects decrease the flame temperature and the convective proportion of the HT. This results in an overall efficiency drop. However, all evaluated models only show a marginal impact of radiation on the global HT; the proportion of radiative HF for both models is approximately 1 % for all evaluated H/D.

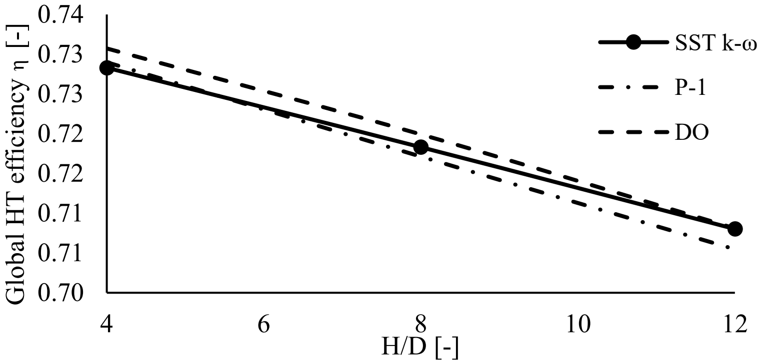


Figure 9: Flame jet impingement heat transfer efficiency excluding and including the P-1 and DO radiation models for different normalized distances H/D.

## 4. Conclusion and outlook

Based on the conducted numerical analysis and the experimental validation, the SST k-ω model and the RSM are considered most relevant for the further analysis or optimizations of flame jet impingement systems in similar configurations. If the efficiency drop for low H/D values is considered relevant, the stress-ω RSM seems to be good approach for RANS modelling. Nevertheless, further analyses to clarify the model's applicability to capture this effect are required. Quantitatively the SST k-ω model can be utilized. For capturing more details, further variations of the k-ω model, more complex hybrid or LES methods need to be investigated. Additionally, the overall model transferability to flames of higher/lower Reynolds number or different torch geometries needs to be verified. Most importantly, further research to understand the physical effects and the model's ability to capture them must be conducted.

Radiation only plays an insignificant role for the HT within flame jet impingement systems at ambient conditions and may therefore be neglected for similar setups.

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