Strömungstechnik

Dominik Denker

Gradient Trajectory Analysis of Reacting Turbulent Flows

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Gradient Trajectory Analysis of Reacting Turbulent Flows

Gradiententrajektorienanalyse von reagierenden turbulenten Strömungen

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

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Dominik Denker

Berichter: Univ.-Prof. Dr.-Ing. Heinz Günter Pitsch
Asst. Prof. Antonio Attili, Ph.D.

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Telefon: 02421 / 99 0 11 - 0 • Telefax: 02421 / 99 0 11 - 9
Internet: www.shaker.de • E-Mail: info@shaker.de

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Zusammenfassung

In dieser Arbeit werden reagierende turbulente Strömungen mit der Dissipations Element (DE) Analyse untersucht. Dies ist eine Gradiententrajektorien basierte Methode zur Unterteilung turbulenter Felder in raumfüllende Unterregionen, in denen sich Skalare monoton verhalten. Im Kontext der Verbrennung ist diese Eigenschaft wichtig, da DEs somit lokal und eindeutig das maximale Ausmaß aufzeigen, welches eine von diffusivem Transport dominierte Struktur, wie z.B. eine Flamme, in einer turbulenten Strömung potentiell einnehmen kann.

Zuerst wird die DE-Analyse auf das Mischungsbruchfeld Z aus direkten numerischen Simulationen (DNS) von nicht vorgemischten Freistrahlflammen angewandt. Es wird gezeigt, dass sich die normierte DE-Parameterstatistik sowie die charakteristischen Skalierungen der jeweiligen Mittelwertgrößen nicht von innerten turbulenten Strömungen unterscheiden. Zusätzlich wird gezeigt, dass die skalare Dissipationsrate χ mit dem Gradienten der größeren lokalen Strömungstopologie, dem DE-Gradienten g, in Beziehung gesetzt werden kann. Ein DE-Parameter basiertes Regimediagramm für nicht vorgemischte Verbrennung wird eingeführt und verifiziert.

Des weiteren werden nicht-lokale Effekte in DNS von vorgemischten Freistrahlflammen untersucht. Die DE Analyse wird auf die Temperaturfelder T angewendet, welche jedoch im Gegensatz zu Z einen chemischen Quellterm besitzen. Die Selbstähnlichkeit der normierten DE-Längenverteilung bleibt bestehen, jedoch zeigt die Statistik der skalaren Differenz ΔT einen deutlichen Einfluss der Flammenstruktur. In der Flammenstrukturanalyse wird gezeigt, dass die Einführung von Extrempunkten nahe der Flammenfront zu einer signifikanten Verdickung der Vorwärm- und Reaktionszone führt. Dieser Effekt wird quantifiziert und mit der Brenngeschwindigkeit in Beziehung gesetzt.

Abschließend werden die gewonnenen Erkenntnisse bei der Modellierung der Verbrennung genutzt. Die Skalierung und Selbstähnlichkeit der DE-Parameterstatistik werden in einer Methodik für die Vorhersage von Verbrennungsregimen bei nicht vorgemischter Verbrennung verwendet. Diese Methodik wird in Reynolds-gemittelten Navier-Stokes-Simulationen eines PKW-Dieselmotors angewendet. Weiterhin wird ein Modell für die Wahrscheinlichkeitsdichtefunktion von Z eingeführt, welches Effekte von laminaren Bereichen und externer Intermittenz berücksichtigt.

Abstract

In this thesis, reacting turbulent flows are analyzed from a structural point of view using Dissipation Element (DE) analysis, which is a gradient trajectory (GT) based method for compartmentalizing turbulent fields into space filling sub-regions in which scalars behave monotonically. In the context of combustion, this property is important, as DEs locally and unambiguously indicate the maximum extent a diffusive transport dominated structure, such as a flame, can potentially occupy in a turbulent flow.

First, DE analysis is applied to the mixture fraction field Z of a series of direct numerical simulations (DNS) of non-premixed jet flames. In a statistical investigation, it is shown that the normalized DE parameter statistics as well as the characteristic scalings of the respective mean quantities do not differ from non-reacting turbulent flows and are therefore unaffected by the heat release. Additionally, it is demonstrated that the scalar dissipation rate χ can be related to the gradient of the larger local flow topology as represented by the DE gradient g. The DE parameters are then used in the construction of a regime diagram for non-premixed combustion which is verified by the DNS results.

Secondly, non-local effects in DNS of premixed combustion are investigated in a series of spatially evolving jet flames. DE analysis is applied to the temperature fields T which, contrary to Z, possess a chemical source term. The self-similarity of the normalized DE length distribution is retained, but the statistics of the scalar difference ΔT show a clear influence of the flame structure. In the consecutive GT based flame structure analysis, it is shown that the introduction of extremal points close to the flame front leads to a significant thickening of both the preheating and inner reaction zone. This effect is quantified and related to the turbulent burning velocity.

Finally, the insights gained are used in combustion modelling. The scaling and self-similarity of the DE parameter statistics are used in a framework for the prediction of combustion regimes in non-premixed combustion. This framework is applied in the Reynolds averaged Navier-Stokes simulation of a passenger car diesel engine. Further, a novel model for the probability density function of Z is presented, which considers effects of laminar regions and external intermittency.

Publications

This thesis is mainly based on the following publications in scientific journals and a book chapter.

- D. Denker et al. “Dissipation element analysis of premixed jet flames”. In: *Comb. Sci. Tech.* 191.9 (2019), pp. 1677–1683.
- D. Denker, A. Attili, and H. Pitsch. “Dissipation Element Analysis of Inert and Reacting Turbulent Flows”. In: *Data Analysis for Direct Numerical Simulations of Turbulent Combustion.* Ed. by H. Pitsch and A. Attili. Springer International Publishing, 2020. Chap. 2, pp. 19–41.
- D. Denker et al. “A New Modeling Approach for Mixture Fraction Statistics Based on Dissipation Elements”. In: *Proc. Comb. Inst* (2020).
- D. Denker et al. “Gradient Trajectory Analysis of the Burning Rate in Turbulent Premixed Jet Flames”. In: *Comb. Sc. and Tech.* 192.11 (2020), pp. 2189–2207.
- D. Denker et al. “Dissipation Element Analysis of Non-premixed Jet Flames”. In: *J. Fluid Mech.* 905 (2020), A4.

Additionally, the following journal publications were contributed during my time at the Institute for Combustion Technology:

- J. Boschung et al. “Finite Reynolds number corrections to the 4/5-law for decaying turbulence”. In: *Phys. Rev. Fluids* 1.064403 (2016).
- J. Boschung et al. “Analysis of structure function equations up to the seventh order”. In: *J. Turbul.* (2017), pp. 1–32.
- A. Schnorr et al. “Feature Tracking by Two-Step Optimization”. In: *IEEE Transactions on Visualization and Computer Graphics* (2018).
- M. Bode et al. “Using Physics-Informed Super-Resolution Generative Adversarial Networks for Subgrid Modeling in Turbulent Reactive Flows”. In: *Proc. Comb. Inst.* (2020).

- M. Gauding et al. "On the combined effect of internal and external intermittency in turbulent non-premixed jet flames". In: *Proc. Comb. Inst.* (2020).
- A. Attili et al. "Turbulent flame speed and reaction layer thickening in premixed jet flames at constant Karlovitz and increasing Reynolds numbers". In: *Proc. Comb. Institute* (2020).

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