

# STUDY OF FLOW AND COMBUSTION IN TECHNICAL COMBUSTION SYSTEMS USING UNSTEADY COMPUTATION TECHNIQUES

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## INHALT

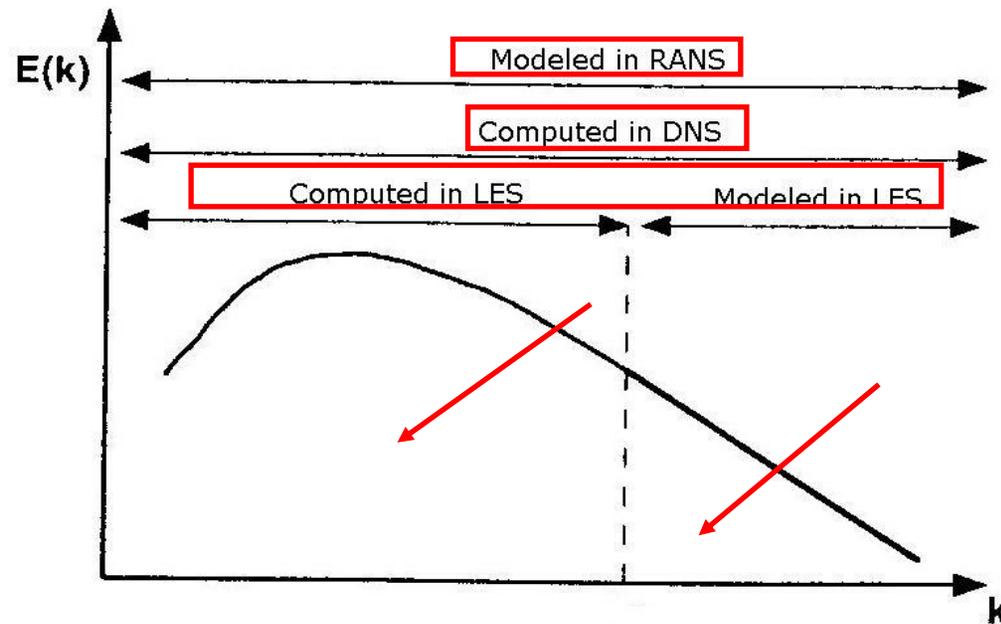
- Motivation
- Strategie der Modellierung
- Anwendungsbeispiele

# → Technische Verbrennungssysteme:

Komplex wechselwirkende Vorgänge/Prozesse

- Turbulenz
- Wärme- und Stofftransport, Turbulente Mischung
- Phaseninteraktionen bzw. -übergang
- Chemische Reaktionen bzw. Verbrennung/Strahlung

## *Klassisches Energiespektrum einer turbulenten Strömung*



# Strategie der Modellierung

- Reynolds/Favre Mittelung/Filterung:  $R_{ij}$ : Reynolds-Stresstensor/SGS-Stresstensor  
 $J_i$ : Skalarfluss-Vektor/SGS-Skalarfluss  
 $Q$ : Chemischer Quellterm

Einphasige Strömungssysteme:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_j) = 0$$

$$\frac{\partial}{\partial t} (\bar{\rho} \tilde{u}_i) = -\frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_i \tilde{u}_j) - \frac{\partial \bar{p}}{\partial x_i} + \bar{\rho} g_i + \frac{\partial}{\partial x_j} \left[ \tilde{\mu} \left( \frac{\partial \tilde{u}_j}{\partial x_i} + \frac{\partial \tilde{u}_i}{\partial x_j} \right) - \frac{2}{3} \tilde{\mu} \frac{\partial \tilde{u}_k}{\partial x_k} \delta_{ij} + \bar{\rho} R_{ij} \right]$$

$$\frac{\partial}{\partial t} (\bar{\rho} \tilde{c}) = -\frac{\partial}{\partial x_j} (\bar{\rho} \tilde{c} \tilde{u}_j) - \frac{\partial}{\partial x_j} \left[ \tilde{D} \left( \frac{\partial \tilde{c}}{\partial x_i} \right) + \bar{\rho} J_j \right] + Q$$

$$\frac{\partial}{\partial t} (\bar{\rho} \tilde{k}) + \frac{\partial}{\partial x_i} (\bar{\rho} \tilde{u}_i \tilde{k}) = P + Dis + Dif ; \quad \dot{\tilde{\varepsilon}} = \dots$$

# Strategie: Thermodynamische Konsistenz

➤ Entropie-Ungleichung/Auswertung:

$$\begin{aligned} \rho \dot{\eta} + \varphi_{i,i} - \sigma^{entr} - \sum_{\beta=1}^{n+1} \Lambda^{\rho^{\beta}} (\text{Masse}) - \sum_{\beta=1}^{n+1} \Lambda^{\bar{v}_i^{\beta}} (\text{Impuls}) \\ - \sum_{\beta=1}^{n+1} \Lambda^{\bar{e}^{\beta}} (\text{Inn. Energie / Enthalpie}) - \sum_{\beta=1}^{n+1} \Lambda^{c^{\beta}} (\text{Spezies}) \\ - \sum_{\beta=1}^{n+1} \Lambda^{T_{ij}} (\text{Spannung}) - \sum_{\beta=1}^{n+1} \Lambda^{J_j} (\text{Skalarfl.}) - \sum_{\beta=1}^{n+1} \dots \geq 0 \end{aligned}$$

Konsistente Kopplung wechselwirkender Mechanismen/Prozesse

- Optimierung von Systemen/Prozessen
- Optimierung von Submodellen und Gesamtmodellen  
( $R_{ij}$ ,  $J_i$ ,  $Q$ ,.....)

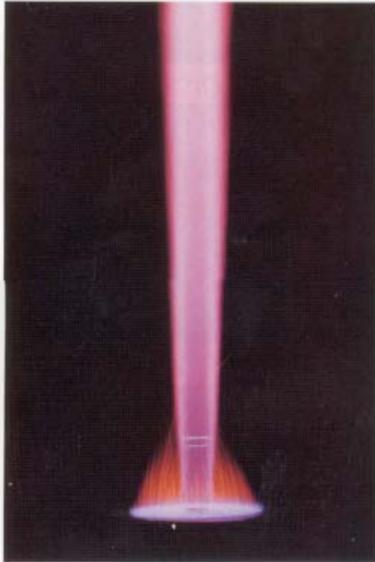
# Anwendungsbeispiele

————— Komplexität, Anwendung —————>

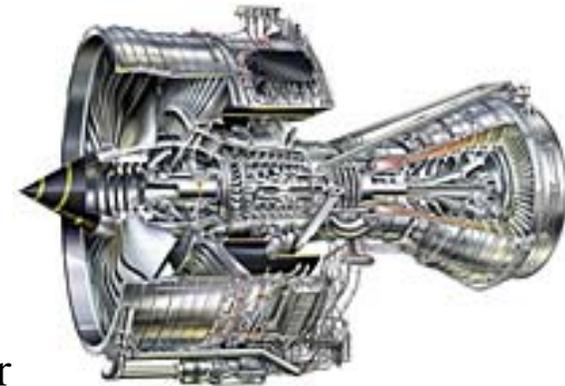
Offene Drallflamme



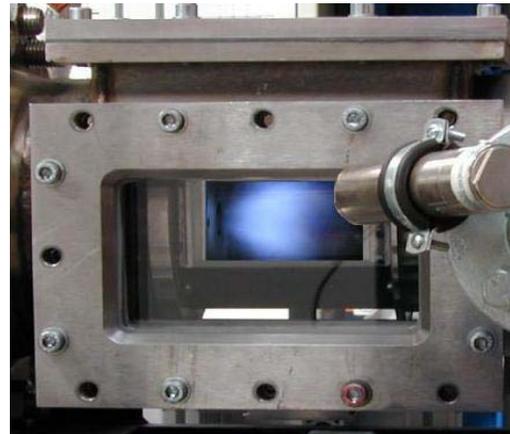
Pilotierte Jet-Flammen



GT-Brennkammer



Modellbrennkammer

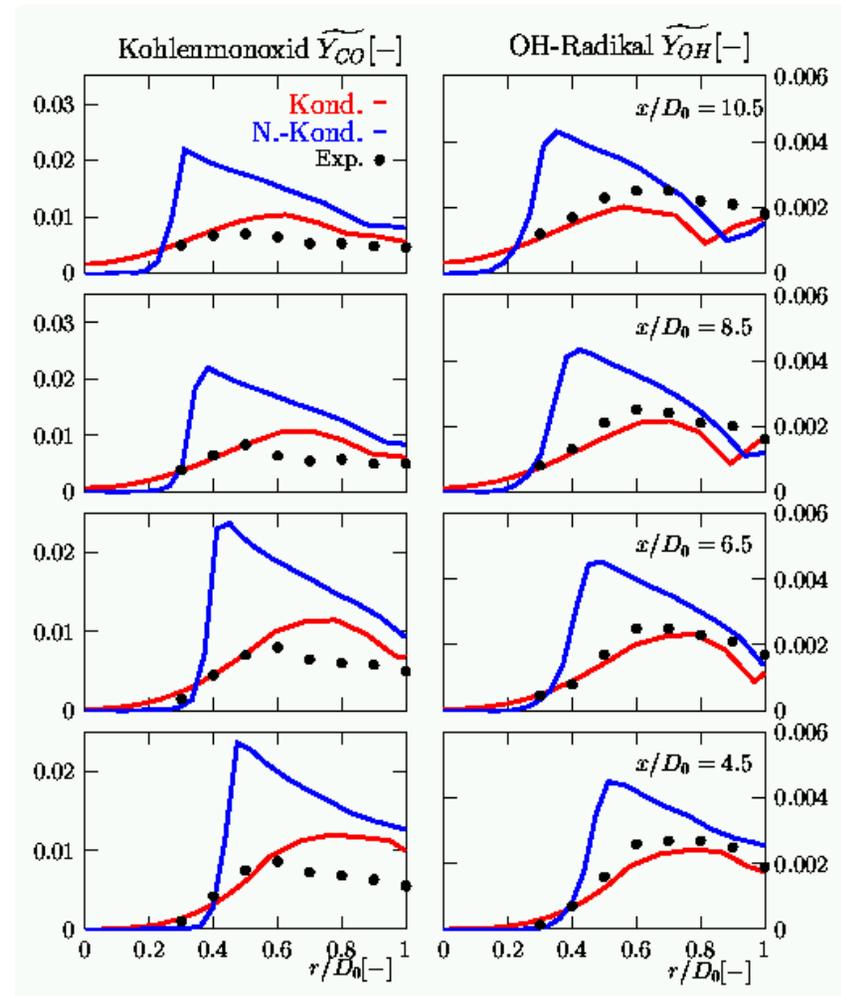
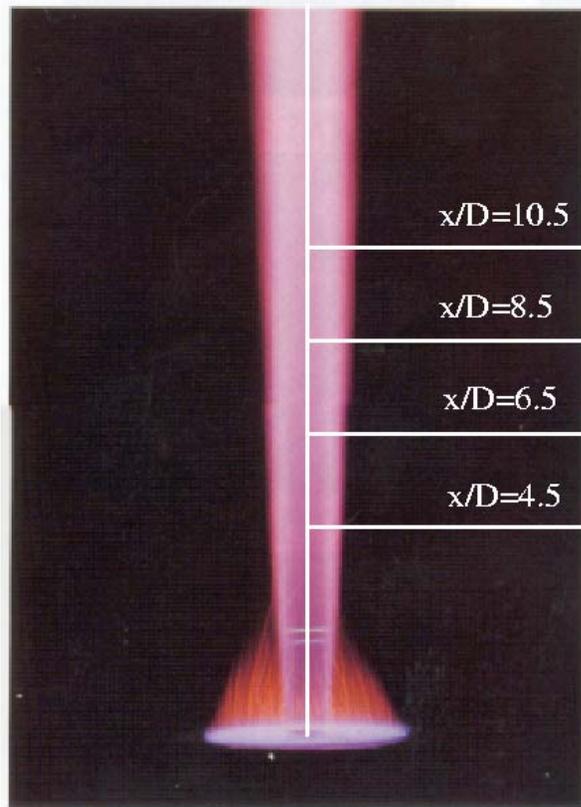


# RANS von einfachen Systemen:

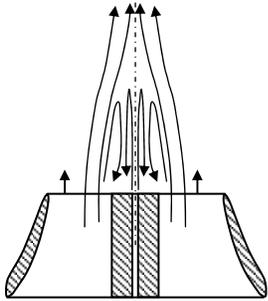
## CHEN Flamme (F2): Vorgemischte Flamme

Verbrennung: Mod. BML, ILDM-PDF, CPVA

Turbulenz: Reynolds-Stress-Transport, Skalarflusstransport



# LES von einfachen Systemen



## Sydney bluff-body burner

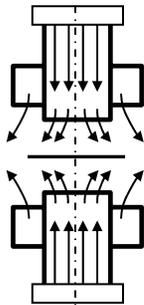
CH<sub>4</sub>/H<sub>2</sub>, 50/50 vol.

108 m/s, 35 m/s

$1,54 \cdot 10^6$  nodes

(Sydney, Sandia, EKT)

➔ *TNF 6, 2002*



## Opposed Jet

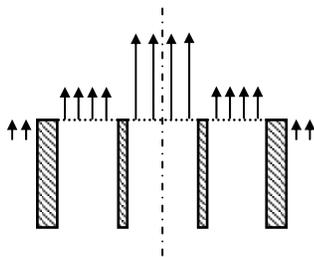
CH<sub>4</sub>/Air, 17,4/82,6 vol.

3,4 m/s, 3,65 m/s,  $Re=6650$

$2,7 \cdot 10^6$  nodes

(Geyer, Nauert)

➔ *30th Comb. Symp.*



## Flame D (pilot-jet-flame)

CH<sub>4</sub>/Air, 25/75 vol.

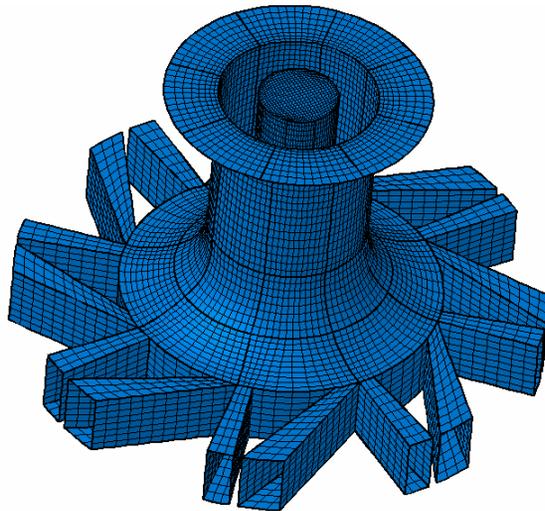
49,6 m/s, 11,4 m/s, 0,9 m/s,  $Re=22400$

$1,97 \cdot 10^6$  nodes

(Sydney, Sandia, EKT) ➔ *30th Comb. Symp.*

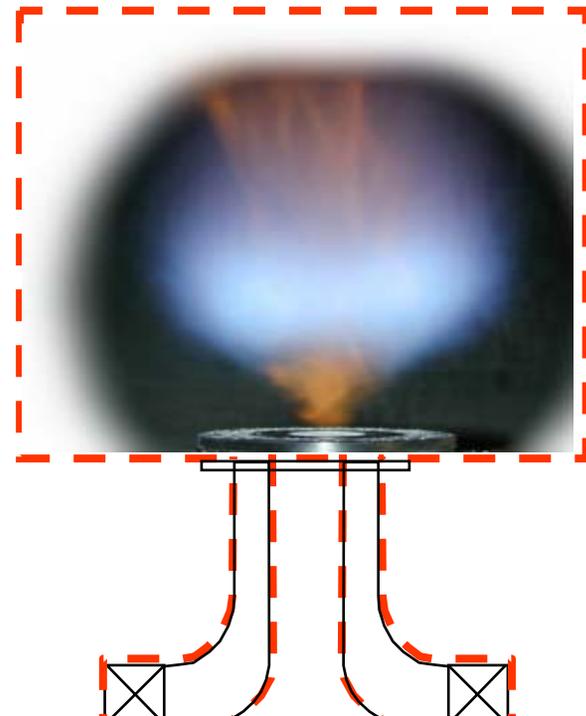
# LES/URANS für Drallströmungen

- Vormischflamme
- Hydrodynamische Instabilität  
(isotherm,  $Re=45729$ )  
*("precessing vortex core")*
- Drall-Zahl 0.75
- $Re = 10000-50000$ ;  
(reagierend/Methan-Luft:  $Re: 42066$ )



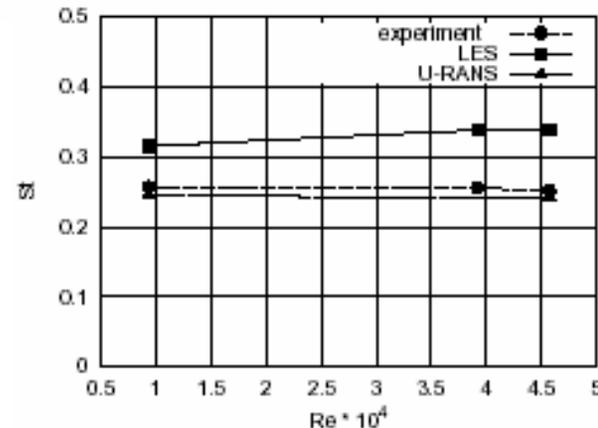
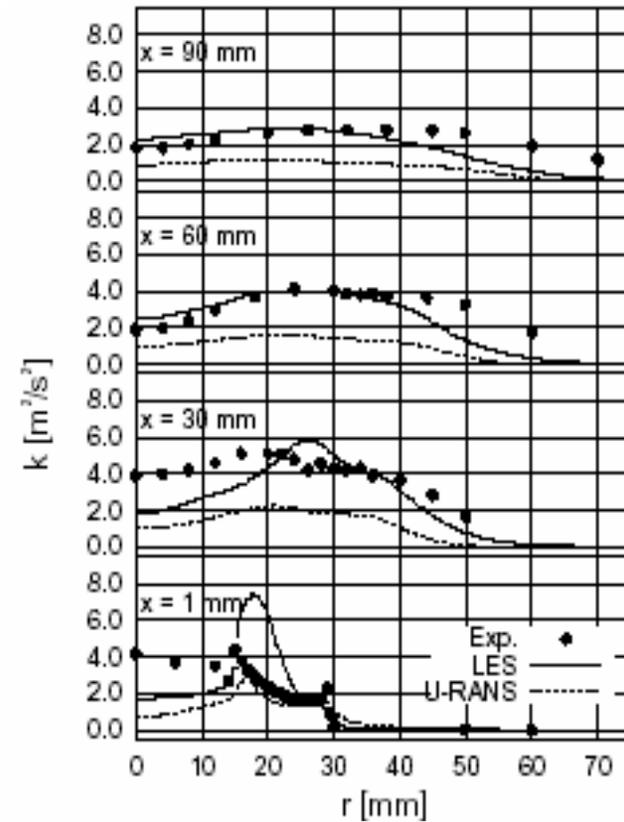
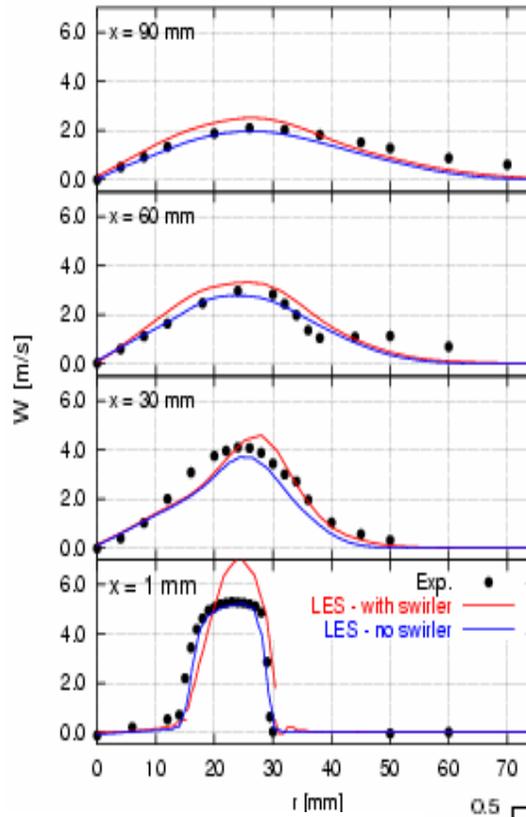
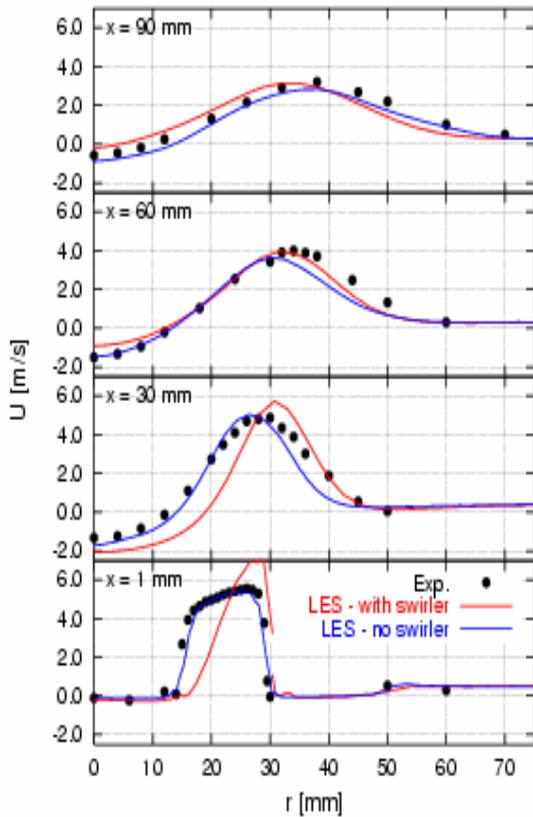
## LES/URANS mit FASTEST-3D:

- dynamisches Smagorinsky-Modell/ RST+SFT
- ca. 800 000 Zellen/700 000
- numerische Abbildung des Drallerzeugers
- Mod. BML; ILDM-PDF; CPVA

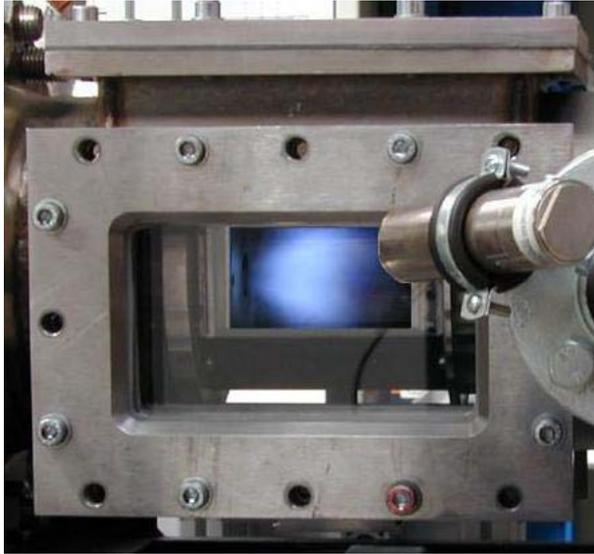


# LES/URANS für Drallströmungen

Axialgeschwindigkeit    Tangentialgeschwindigkeit



# LES/URANS für Modellbrennkammer



→ Messungen: B. Janus 2003

→ Geschwindigkeit: LDA

→ PLIF-OH-Visualisierung

→ Druck  $p=2\text{bar}$

→ Methan:  $T_{\text{Methan}}=40^\circ\text{C}$ ,

$Re_{\text{Methan}}=40800$

→ Luft:  $T_{\text{Luft}}=330^\circ\text{C}$ ,

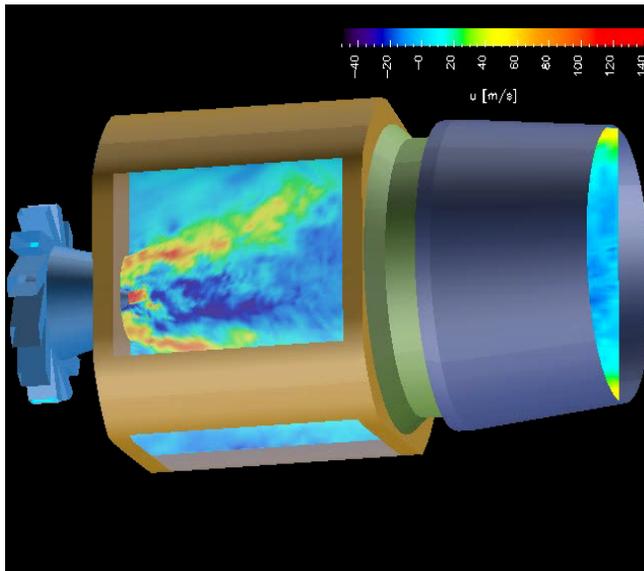
$Re_{\text{Luft}}=46000$

→ Fall 1: Isotherm

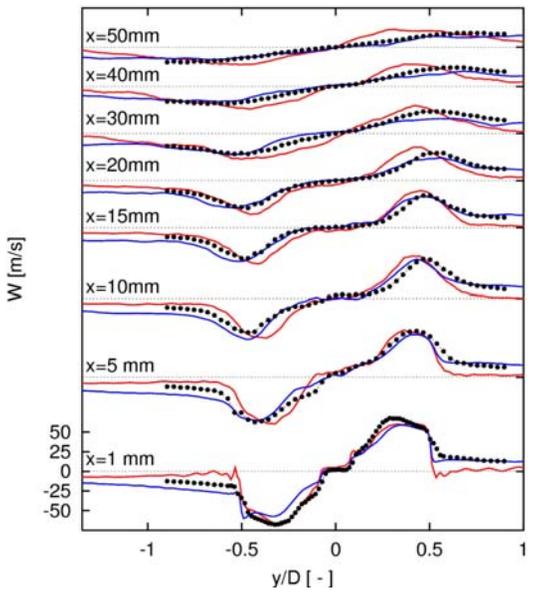
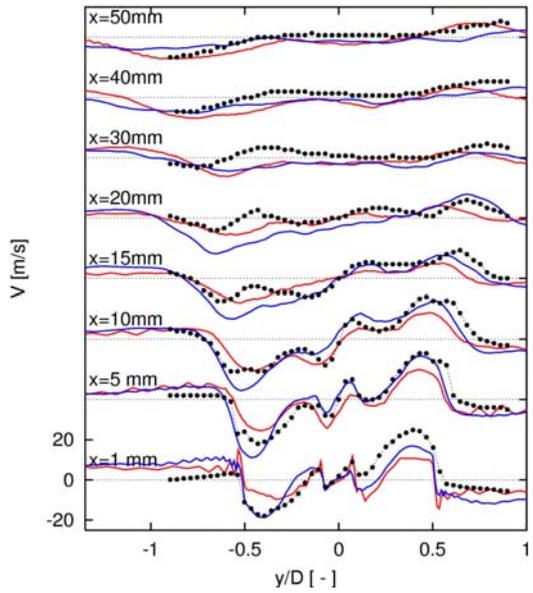
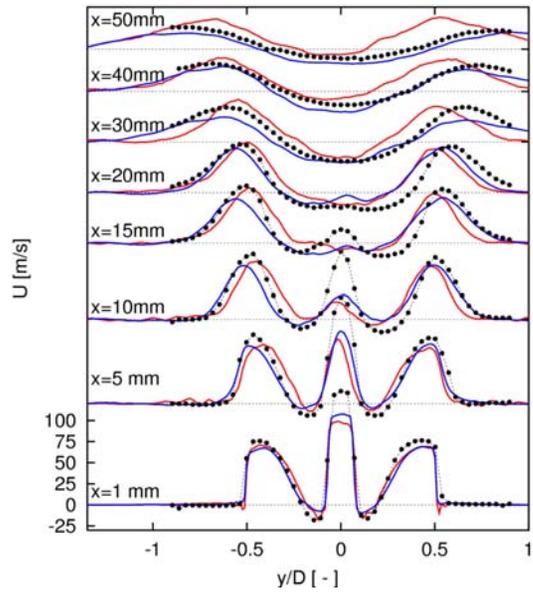
(Luft/Helium statt Methan)

→ Fall 2: Reagierend

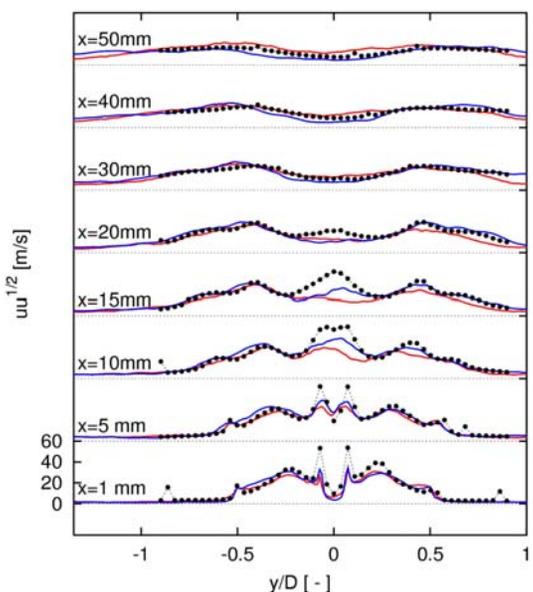
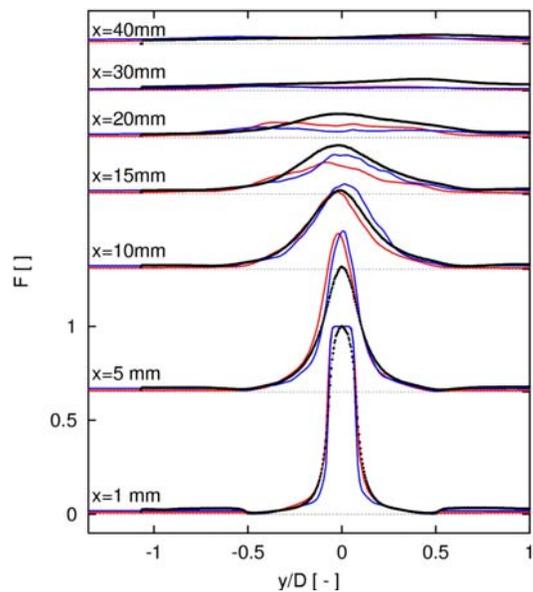
- Turbomeca Swirler (*MOLECULES* - Testfall)
- LES auf 2 Gittern (2.4 M Zellen bzw. 2.4 M Zellen / 8)
- Dynamisches Smagorinsky-Modell
- Verbrennung: Mod. BML, CPVA
- Drallerzeuger aufgelöst



# LES: Druckbrennkammer



(Wegner 2004)

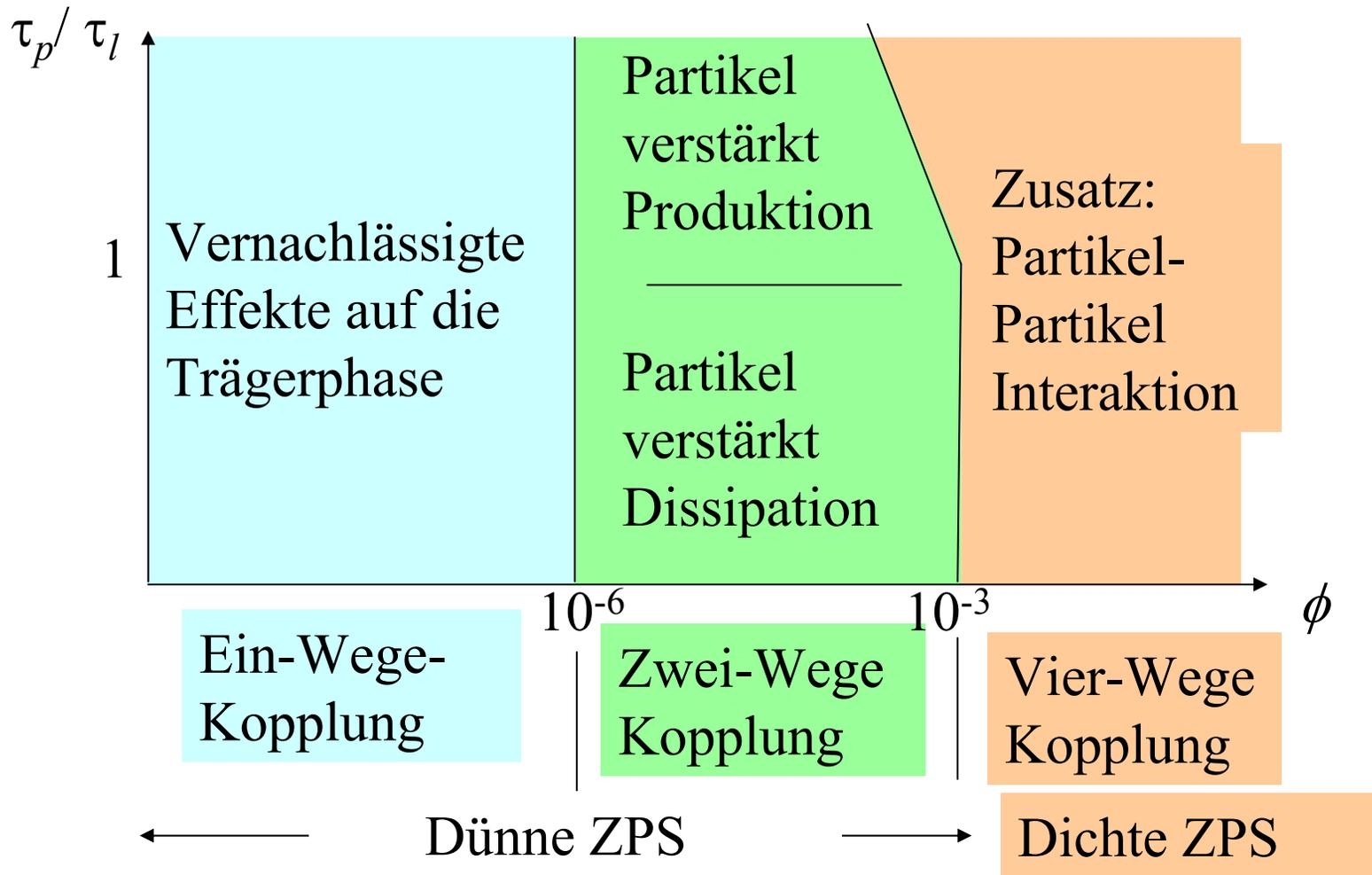


- • - • - Exp. (LDA/PLIF)
- LES - grob
- LES - fein

# Mikroprozesse in Fluid-Partikel -Strömungssystemen:

Trägerphase: *Gas/Flüssigkeit*

Disperse Phase: *Poly-disperse Partikel*



# Modulationsmodelle: $S_{\phi,p}$

## (1) Standard Ansatz

$$k : \overline{u_i S_{u_i,p}} - \overline{u_i S_{u_i,p}}$$

$$\varepsilon : c_{\varepsilon,3} \frac{\varepsilon}{k} S_{k,p}$$

## (2) Crowe Modulation Modell (basiert auf Energie Bilanz) (1998/2000)

$$S_{k,p} = \left( \overline{u_{pi} S_{u_i,p}} - \overline{u_i S_{u_i,p}} \right)$$

## (3) Thermodynamisch konsistente Modellierung (Sadiki & Ahmadi , (2002)

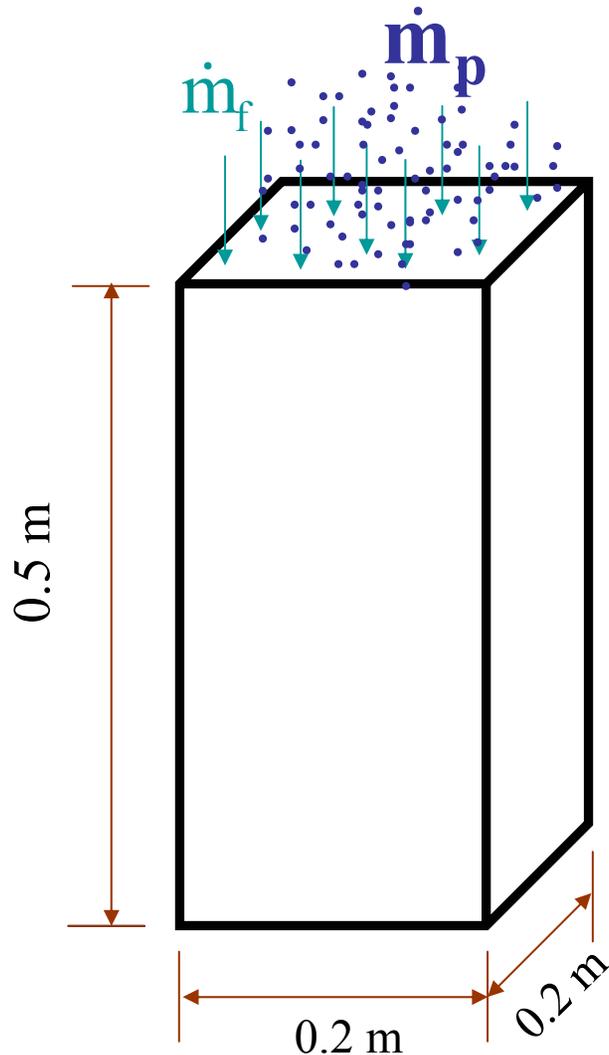
$$S_{k,p} = \beta \left( \overline{u_{pi} S_{u_i,p}} - \overline{u_i S_{u_i,p}} \right) + \left( \overline{u_i S_{u_i,p}} - \overline{u_i S_{u_i,p}} \right)$$

$$\beta = \alpha' + \frac{(1 - \alpha') \left( \overline{u_{pi} S_{u_i,p}} - \overline{u_{pi} S_{u_i,p}} \right)}{\left( \overline{u_{pi} S_{u_i,p}} - \overline{u_i S_{u_i,p}} \right)}$$

# Anwendung I: Dünnes Gas-Feststoff-System

Ziel: Erfassung der Turbulenz-Modulation

A.- Partikelbeladene, vertikale Kanalströmung (Geiss et al. 2002)



## Eintrittsbedingungen:

$$U_m = 10 \text{ m/s,}$$

$$k = 0.735 \text{ m}^2/\text{s}^2,$$

$$\varepsilon = 110 \text{ m}^2/\text{s}^3$$

$$KV = 84000 \text{ (64x36x36)}$$

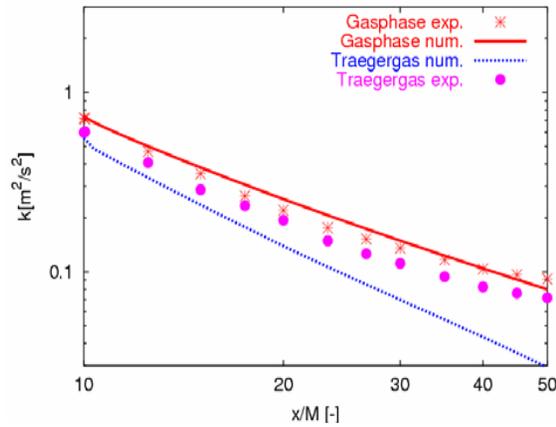
Partikeldurchmesser:

120; 240; 480 [micro]

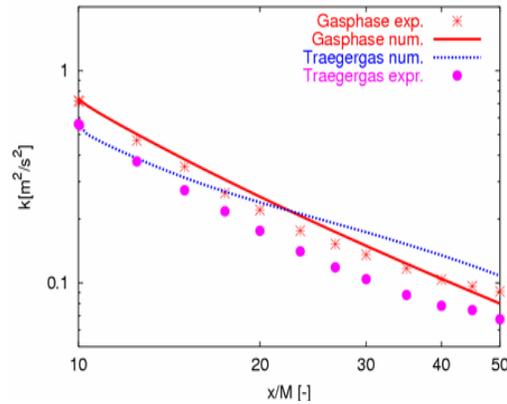
Volumenbruch:

25 ; 45 ; 90 ; 70 ; 8 [P./ccm]

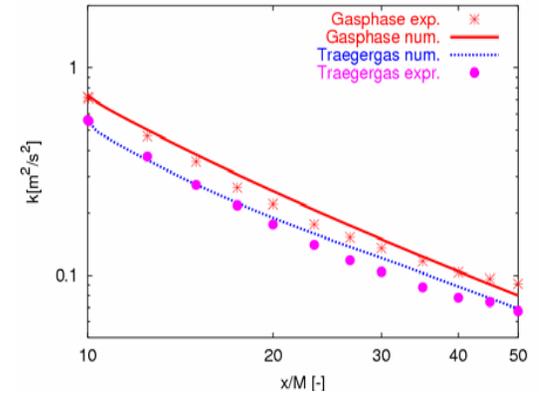
## Standard-Ansatz



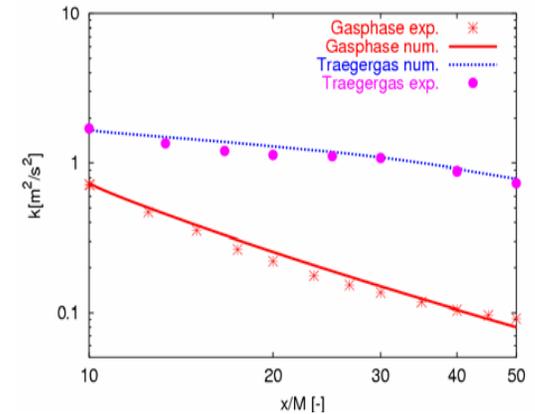
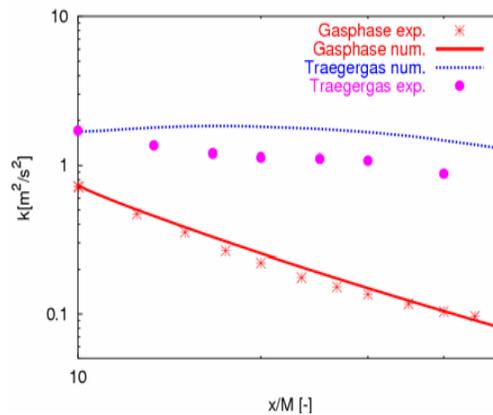
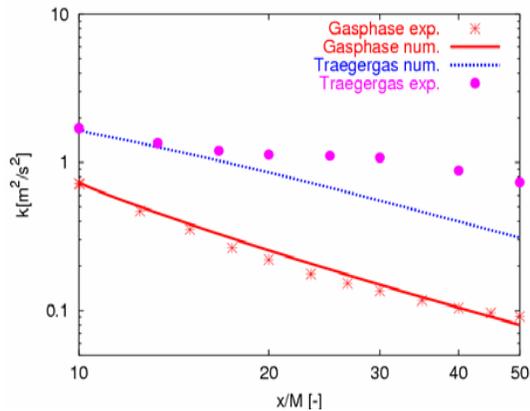
## Crowe-Modell (basiert auf Energiebilanz)



## Sadiki & Ahmadi Modell (2002)



(d=120 micro)



(d=480 micro)

# Arbeitsfelder am Institut EKT (u.a. Modellierung, Numerische Berechnungen, Validierung)

