# Thermo-Fluid Dynamics

**Modelling and simulation of thermo-fluid dynamic phenomena in energy and process technology**

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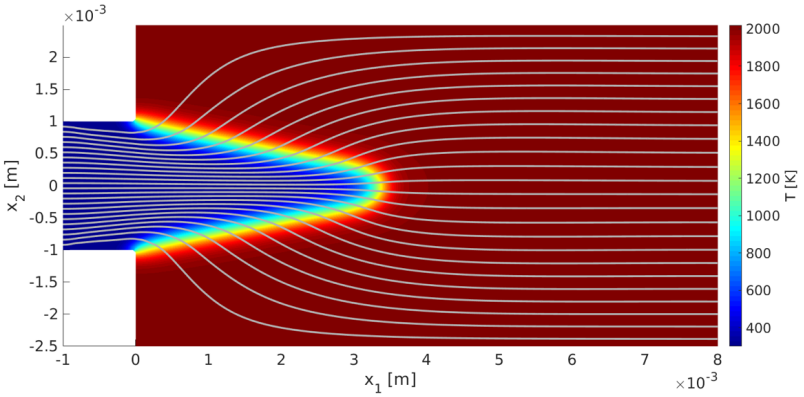
*In 2016 important results on intrinsic thermoacoustic feedback and advective waves in combustion dynamics and combustion noise were obtained. The formulation of interconnected state space models for (thermo-)acoustic phenomena made significant progress.*

**Highlights**

- Ralf Blumenthal was awarded the Dissertation Prize of the Faculty of Mechanical Engineering for his doctoral thesis 'A systems view on non-normal transient growth in thermoacoustics'
- Extended visit by Prof. José Velasquez (UTFPR, Brazil) since March
- Wolfgang Polifke served as Chair of the Colloquium 'Gas Turbine Combustion' at the '36th Int. Symposium on Combustion' and was appointed member of the editorial board of 'Combustion and Flame'

## Advective Waves

We have revisited the conservation equations of mass, momentum and energy across a moving premixed flame front and could thus resolve some paradoxical results concerning the coupling conditions across a flame in the limit of zero Mach number and the generation of entropy waves by a flame.




*Stream lines across a premix flame front. Advective/diffusive dispersion of entropy waves develops along the stream lines (from Strobio et al, ASME, 2016)*

An analytical, time-domain model for the response of premixed flames to fuel inhomogeneities was formulated, which provides insight into the important interactions between convective transport of fuel and the kinematic balance at a propagating flame. Furthermore, it was shown that perturbations of swirl in a premix duct are inertial waves, which propagate at a speed that is not equal to the mean flow velocity. These investigations of flow-flame-acoustic interactions are of a fundamental nature, but provide important information for the proper formulation of analysis and design tools for thermoacoustic stability.

**Key Publications**

- Strobio Chen, L., Bomberg, S., Polifke, W., 2016. Propagation and Generation of Acoustic and Entropy Waves Across a Moving Flame Front. Comb. and Flame 166, 170-180
- Strobio Chen, L., Steinbacher, T., Silva, C., Polifke, W., 2016. On Generation of Entropy Waves Across a Premixed Flame, GT2016-57026, in: Proceedings of ASME 2016 Turbo Expo, Seoul, Korea
- Albayrak, A., Blumenthal, R.S., Ulhaq, A., Polifke, W., 2016. An Analytical Model for the Impulse Response of Laminar Premixed Flames to Equivalence Ratio Perturbations, in: 36th Int. Symposium on Combustion. Combustion Institute. doi:10.1016/j.proci.2016.06.002
- Albayrak, A., Polifke, W., 2016. Propagation Velocity of Inertial Waves in Cylindrical Swirling Flow, 23nd Int. Congress on Sound and Vibration (ICSV23). IIAV, Athens, Greece.

**Projects**

- Marie Curie FP7 IPN TANGO, FVV

## Interconnected State-Space Models for Thermo- and Aero-Acoustics

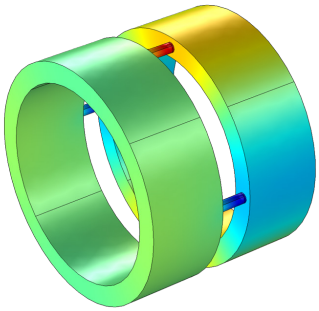
Continued efforts to develop a state-space-based modelling framework for generation, transmission and scattering of sound in ducted configurations made very significant progress in 2016. The in-house toolbox taX provides a user-friendly framework for the monolithic integration of a wide range of models. The use of sparse matrix techniques combined with the discontinuous Galerkin method for acoustic perturbation equations yields unprecedented speed, memory efficiency, accuracy and robustness. Generation, propagation and dissipation of sound in combustion chambers, ventilation ducts or exhaust systems as well as related instabilities may now be modelled in a flexible and very efficient manner.

**Key Publications**

- Emmert, T., Meindl, M., Jaensch, S., Polifke, W., 2016b. Linear State Space Interconnect Modelling of Acoustic Systems. Ac0at Acustica united with Acustica 102, 824-833.
- Meindl, M., Emmert, T., Polifke, W., 2016. Efficient calculation of thermo-acoustic modes utilizing state-space models, 23nd Int. Congress on Sound and Vibration (ICSV23). Athens, Greece.

**Projects**

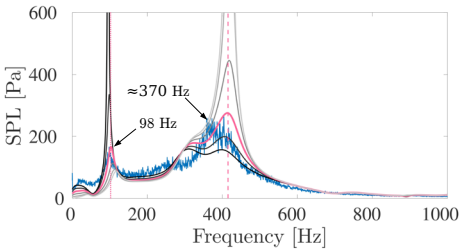
- FVV, SFB/TRR40



*Acoustic eigenmode in an annular topology computed with taX (from Meindl et al., ICSV23, 2016)*

## Intrinsic Thermoacoustic Feedback

In 2015, seminal results on intrinsic thermoacoustic feedback in anechoic combustors were published by our group. Subsequent work explored the impact on broadband combustion noise on the one hand, and the stability of combustion chambers with non-zero reflection coefficients on the other. In both cases, our results show that intrinsic modes will in general play an important role in combustion dynamics also for configurations of applied interest, with possibly profound consequences for passive control strategies.




*Power spectral distribution of pressure fluctuations in turbulent combustor. The peak at 98 Hz results from intrinsic resonance and shows anomalous response to variation in the exit reflection coefficient Rx (from Silva et al, TIGRE, 2016)*

**Key Publications**

- Emmert, T., Bomberg, S., Jaensch, S., Polifke, W., 2016a. Acoustic and Intrinsic Thermoacoustic Modes of a Premixed Combustor, in: 36th Int. Symposium on Combustion. Combustion Institute, Seoul, Korea. doi:10.1016/j.proci.2016.08.002
- Silva, C.F., Merk, M., Komarek, T., Polifke, W., 2016. The Contribution of Intrinsic Thermoacoustic Feedback to Combustion Noise and Resonances of a Confined Turbulent Premixed Flame, in: Thermoacoustic Instabilities in Gas Turbines and Rocket Engines. Garching, Germany.

**Projects**

- Marie Curie FP7 IPN FlowAirs, DFG/ANR NoiseDyn,

**Research Focus**

- Combustion dynamics
- Thermo- and aero-acoustics
- Stability analysis
- Mixing and reaction in turbulent flows
- Polydisperse multi-phase flows

**Competence**

- Thermo-fluid dynamics
- Combustion modeling
- Large-eddy simulation
- System identification
- Stability analysis
- Low-order acoustic modeling

**Infrastructure**

- Compute cluster

**Courses**

- Engineering Thermodynamics
- Wärmetransportphänomene
- Wärme- und Stoffübertragung
- Grundlagen der Mehrphasenströmung
- Grundlagen der numerischen TFD
- Computational Thermo-Fluid Dynamics
- Simulation of Thermofluids with Open-Source Tools

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Dipl.Ing. (FH) Sigrid Schulz-Reichwald

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Camilo Silva, Ph.D.
Carlo Sovardi, M.Sc.
Dipl.-Ing. Thomas Steinbacher
Lin Strobio Chen, M.Sc.
Dipl.-Ing. Armin Witte

# Publications 2016


- Achury, J., Polifke, W., 2016. Theoretical investigation of the particle response to an acoustic field. Int. J. Spray Comb. Dynamics. doi:10.1177/1756827716641118
- Achury, J., Polifke, W., 2016c. Modulation of spray droplet number density and size distribution by an Acoustic Field, in: International Conference on Multiphase Flow 2016. Florence, Italy.
- Albayrak, A., Blumenthal, R.S., Ulhaq, A., Polifke, W., 2016. An Analytical Model for the Impulse Response of Laminar Premixed Flames to Equivalence Ratio Perturbations, in: 36th Int. Symposium on Combustion. Combustion Institute. doi:10.1016/j.proci.2016.06.002
- Albayrak, A., Polifke, W., 2016. Propagation Velocity of Inertial Waves in Cylindrical Swirling Flow, in: 23nd Int. Congress on Sound and Vibration (ICSV23). IIAV, Athens, Greece.
- Blumenthal, R.S., Tangirala, A.K., Sujith, R.I., Polifke, W., 2016. A systems perspective on non-normality in low-order thermoacoustic models: full norms, semi-norms and transient growth. Int. J. Spray Combust. Dyn. doi:10.1177/1756827716652474
- Bodén, H., Polifke, W., 2016. Uncertainty quantification applied to aeroacoustic predictions, in: Schram, C. (Ed.), Progress in Simulation, Control and Reduction of Ventilation Noise, VKI Lecture Series 2015. Rhode-St-Genèse, BE.
- Caeiro, F., Sovardi, C., Förner, K., Polifke, W., 2016b. Shape Optimisation of a Helmholtz Resonator using the Adjoint Method, in: Int. Symp. on Thermoacoustic Instabilities in Gas Turbines and Rocket. Garching, Germany.
- Emmert, T., 2016. State Space Modeling of Thermoacoustic Systems with Application to Intrinsic Feedback (Ph.D. Thesis). TU München, Munich, Germany.
- Emmert, T., Bomberg, S., Jaensch, S., Polifke, W., 2016a. Acoustic and Intrinsic Thermoacoustic Modes of a Premixed Combustor, in: 36th Int. Symposium on Combustion. Combustion Institute, Seoul, Korea. doi:10.1016/j.proci.2016.08.002
- Emmert, T., Meindl, M., Jaensch, S., Polifke, W., 2016b. Linear State Space Interconnect Modeling of Acoustic Systems. Acta Acustica united with Acustica 102, 824-833. doi:10.3813/AAA.918997
- Förner, K., Polifke, W., 2016. Nonlinear Aeroacoustic Identification of the Helmholtz Resonator Response Based on a Local Linear Neuro-Fuzzy Model, in: Adams, N.A., Radespiel, R., Sattelmayer, T., Schröder, W., Weigand, B. (Eds.), Annual Report. Sonderforschungsbereich/Transregio 40.
- Förner, K., Tournadre, J., Martínez-Lera, P., Polifke, W., 2016b. Scattering to Higher Harmonics for Quarter Wave and Helmholtz Resonators, in: 22nd AIAA/CEAS Aeroacoustics Conference. Lyon, France. doi:10.2514/6.2016-2968
- Jaensch, S., Merk, M., Gopalakrishnan, E., Bomberg, S., Emmert, T., Sujith, R.I., Polifke, W., 2016a. Hybrid CFD/ low-order modeling of nonlinear thermoacoustic oscillations. Proceedings of the Combustion Institute 36. doi:10.1016/j.proci.2016.08.006
- Jaensch, S., Polifke, W., 2016a. On the uncertainty encountered when modeling self-excited thermoacoustic oscillations with artificial neural networks, in: Int. Symp. on Thermoacoustic Instabilities in Gas Turbines and Rocket Engines, GTRE-006. Garching, Germany.
- Jaensch, S., Polifke, W., 2016. CFD-basierte, Niedrigdimensionale Modellierung der Nichtlinearen Dynamik von Vormischflammen, in: Informationstagung Motoren/Turbomaschinen, R574 / R575. Bad Neuenahrt, Germany.
- Jaensch, S., Sovardi, C., Polifke, W., 2016b. On the robust, flexible and consistent implementation of time domain impedance boundary conditions for compressible flow simulations. J. Comp. Phys 314, 145-159. doi:10.1016/j.jcp.2016.03.010
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- Lee, J.S, Violato, D, Polifke, W, 2016. Experimental investigation on two-phase horizontal intermittent flow through an orifice, in: International Conference on Multiphase Flow (ICMF 2016). Florence, Italy.
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- Lee, J.S., Violato, Daniele, Polifke, Wolfgang, 2016b. Sound generation by bubble dynamics of intermittent horizontal two-phase pipe flow through an orifice, in: 11th International Conference on Flow-Induced Vibration. The Hague, Netherlands.
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- Merk, M., Jaensch, S., Polifke, W., 2016b. On Hydrodynamic Effects During Self-Excited Thermoacoustic Oscillations, in: 24th ICTAM Conference. Montreal, Canada.
- Merk, M., Jaensch, S., Polifke, W., 2016c. Concurrent identification of flame dynamics and combustion noise for turbulent flames, in: CDCN2 – Second Colloquium on Combustion Dynamics and Combustion Noise. Menaggio, Italy.
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- Polifke, W., 2016b. Consequences of Intrinsic Thermoacoustic Feedback for Combustion Dynamics and Combustion Noise, in: CDCN2 – 2nd Colloquium on Combustion Dynamics and Combustion Noise. Menaggio, Italy. doi:10.13140/RG.2.2.20329.29289
- Polifke, W., 2016. Distributed delay and state space models in acoustics and combustion dynamics, in: Linné FLOW Centre, Annual Meeting of the Linné FLOW Centre. Skytteholm, Ekerö, Sweden.

- Rouwenhorst, D., Hermann, J., Polifke, W., 2016a. Online monitoring of thermoacoustic eigenmodes in annular combustion systems based on a state space model, in: Proceedings of ASME 2016 Turbo Expo: Turbomachinery Technical Conference & Exposition, GT2016-56671. Presented at the ASME GT16, ASME, Seoul, Korea. doi:10.1115/GT2016-56671
- Rouwenhorst, D., Hermann, J., Polifke, W., 2016b. Online Monitoring of Thermoacoustic Eigenmodes in Annular Combustion Systems Based on a State-Space Model. J Eng Gas Turb Power, doi:10.1115/1.4034260
- Rouwenhorst, D., Hermann, J., Polifke, W., 2016c. Bifurcation study of azimuthal bulk flow in annular combustion systems with cylindrical symmetry breaking, in: Thermoacoustic Instabilities in Gas Turbines and Rocket Engines, GTRE-010. Garching, Germany.
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- Steinbacher, T., Strobio Chen, L., Polifke, W., 2016. Modeling the generation of entropy waves by a premixed flame, in: CDCN2 – 2nd Colloquium on Combustion Dynamics and Combustion Noise. Menaggio, Italy.
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- Tournadre, J., Förner, K., Polifke, W., Martínez-Lera, P., Desmet, W., 2016b. Determination of Acoustic Impedance for Helmholtz Resonators Through Incompressible Unsteady Flow Simulations. AIAA Journal. doi:10.2514/1.J055337
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- Witte, A., Polifke, W., 2016. Modeling the Heat Transfer and Skin Friction Frequency Response of a Cylinder in Cross-Flow – a Unifying Perspective, in: 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics. Presented at the 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, HEFAT, Malaga, Spain, pp. 1022-1027.