# Stability analysis of reacting wakes: flow and density asymmetry effects

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## Introduction

### Motivation

Combustion instabilities are a leading cause of hardware damage

- Combustion instabilities are poorly understood, particularly when coupled with hydrodynamic stability boundaries
- Bluff body wake is common flame holding technique that is plagued with combustion instability
- Bluff body wake is a simple, canonical flow field, well suited for fundamental combustion instability studies

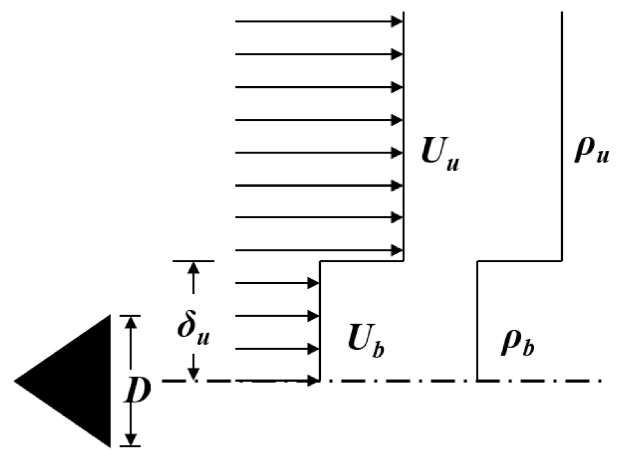



**Figure 1: Velocity and Density profile for reacting bluff body wake (*1*)**

### Bluff Body Flow Dynamics

Unforced bluff body flow fields exhibit Von Karman vortex street

- Vortex street is the flow's natural dynamics- it is a **global instability**
- Consists of alternating vortex shedding
- Vortex shedding occurs at global mode frequency

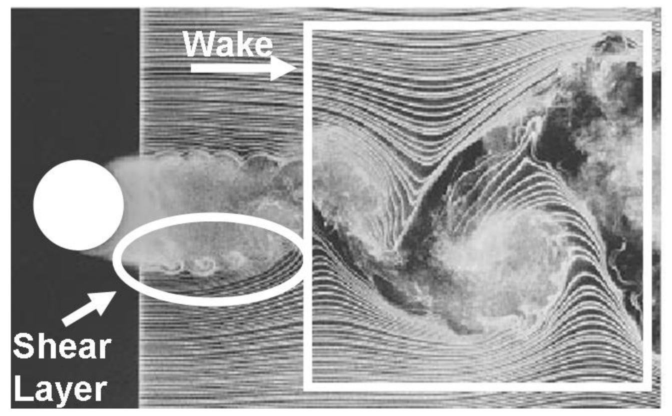



**Figure 2: Nonreacting bluff body flowfield (*2*)**

### Reacting Flow Dynamics

Combustion may suppress the vortex street

- **High density** ratio flames suppress vortex street- flow is **globally stable**
- **Low density** ratio flames permit vortex street- flow is **globally unstable**
- Flame density ratio is a stability parameter
- Flame density ratio is particularly sensitive to preheat

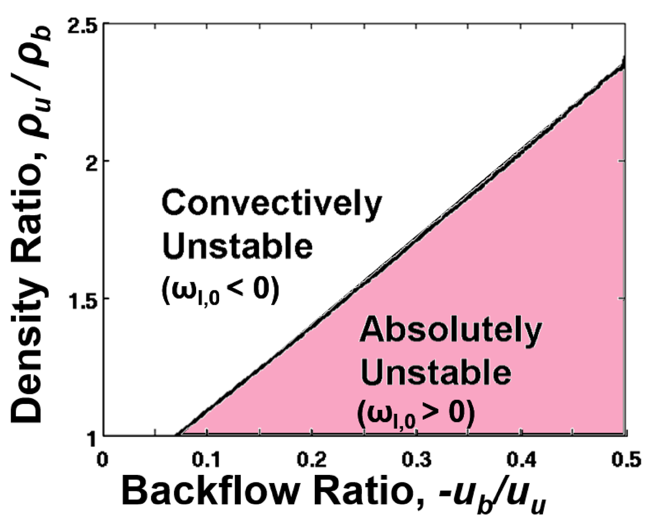



**Figure 3: Global stability domains (*1*)**

## Methods

### Combustor

- Vitiated bluff body burner
- Optically accessible

### Diagnostics

- Measure velocity field with low-speed particle image velocimetry
- Image the flame structure with high speed chemiluminescence.

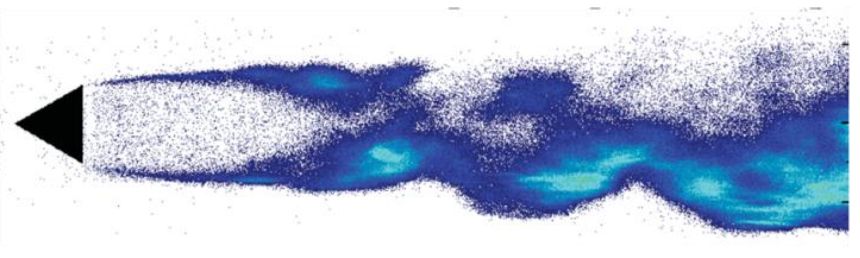


**Figure 4: Reacting bluff body flowfield exhibiting base density asymmetry**

## Objectives

**Determine the effect of base density and velocity asymmetry via parametric stability analysis on:**

1. Global stability of the wake
2. Structure of the hydrodynamic global mode

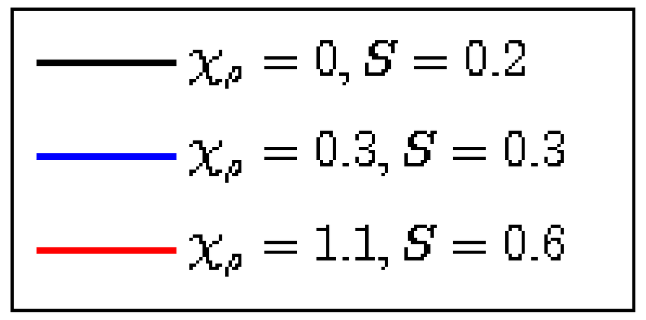
**Compare stability predictions to experimental observations.**

## Results

### Test Conditions

Three cases

- one highly asymmetric condition predicted to be absolutely unstable.



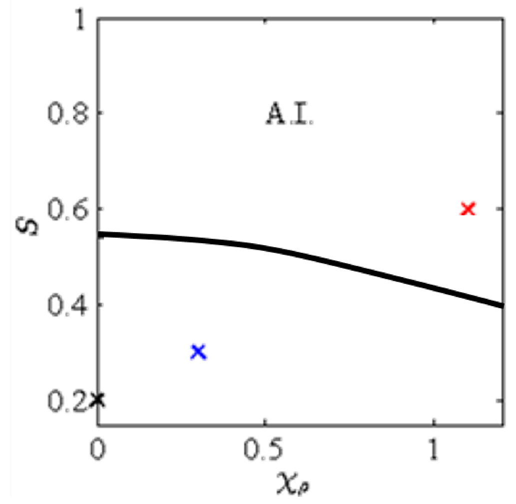




**Figure 6: Experimental test conditions**

### Magnitude of flame flapping

Highest density asymmetry case shows greatest flame flapping

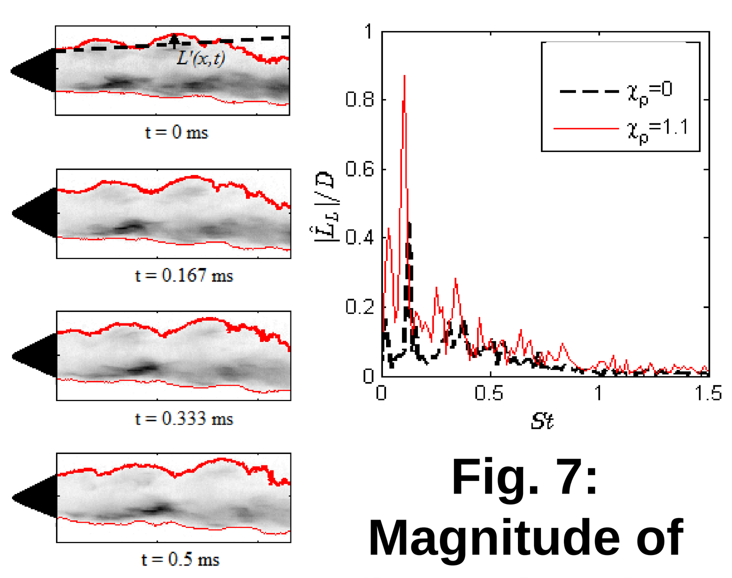



**Fig. 7: Magnitude of flame flapping**

### Flapping of lean vs. rich branches

Highly asymmetric case shows greater oscillations of leaner flame branch.

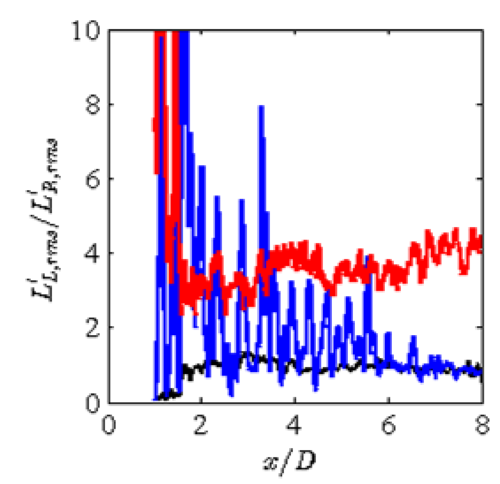



**Figure 8: Flapping of lean/rich branches**

### Observations

1. Base density asymmetry increases absolute growth rate, reduces absolute frequency.
2. Base velocity asymmetry reduces absolute growth rate, increases absolute frequency.
3. Density asymmetry distorts hydrodynamic mode shape.
4. Flame branch with smaller density jump associated with greater hydrodynamic oscillations

## Analysis

### Global stability analysis

Captures important qualitative trends.

- Does not quantitatively describe observed global stability boundaries.
  - Wide range of stability-transition parameters reported in literature.
  - Due to non-colocation of density jump and shear layer.

### Generalized reacting wake model

Permits linearly-stratified base density in bluff body wake

- $S, \chi_\rho$ characterize base density asymmetry.
- $\lambda, \chi_u$ characterize base velocity asymmetry.

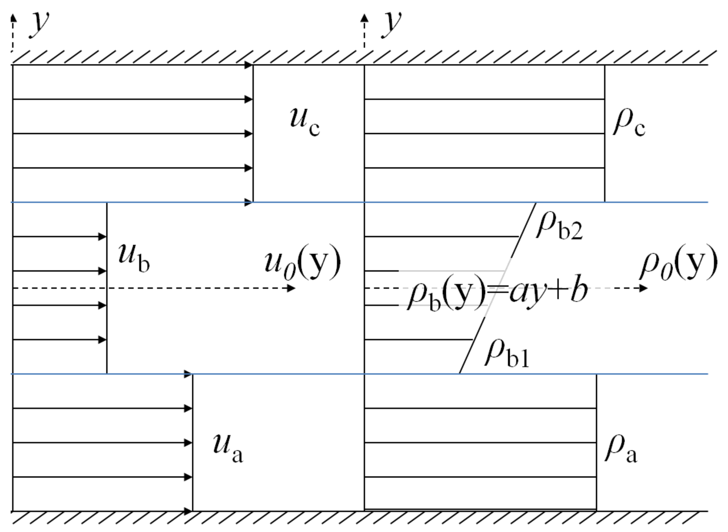



**Figure 9: Generalized model profiles for base velocity (left) and base density (right)**

### Generalized model predictions

Absolute frequency and growth rate strongly affected by base asymmetry.

- Base density (velocity) asymmetry increases (reduces) growth rates, reduces (increases) frequency.

Hydrodynamic mode shapes distorted by density asymmetry.

- Small base density jump associated with large oscillations.

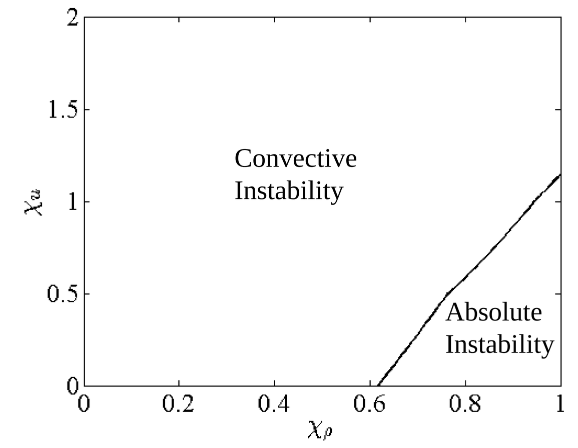



**Figure 10: Predicted generalized global stability domains**

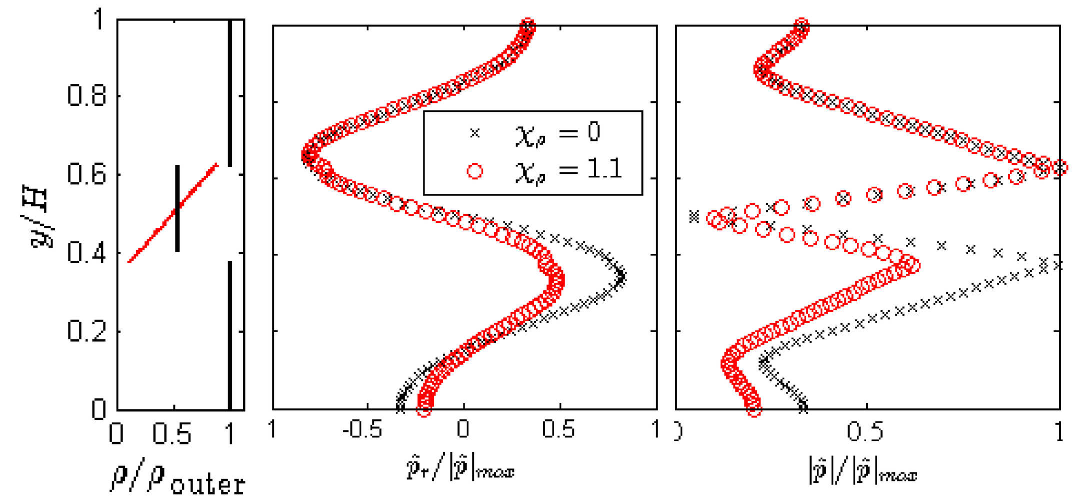



**Figure 11: Hydrodynamic mode shapes with and without asymmetry.**

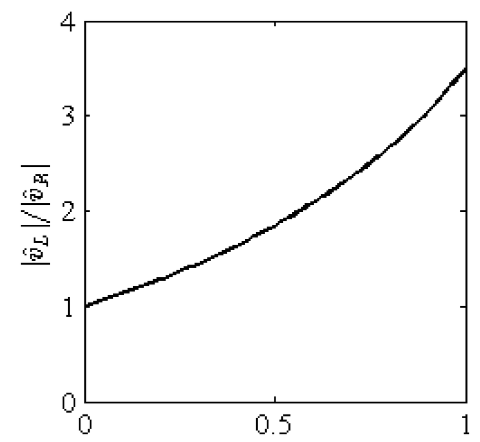



**Fig. 12: Hydrodynamic flapping amplitude predictions**

## Conclusions

1. Base density asymmetry is an important stability parameter.
2. Leaner flame oscillates more with higher base density asymmetry.

**References**
(1) Prasad and Williamson, JFM, 1997
(2) Yu and Monkewitz (Phys. Fluids A 2(7), July 1990)

**References**
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