FLAME IMPINGEMENT IN COMBUSTION PROCESS

COMBUSTION TECHNOLOGY & THERMAL ANALYSIS

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SYLLABUS

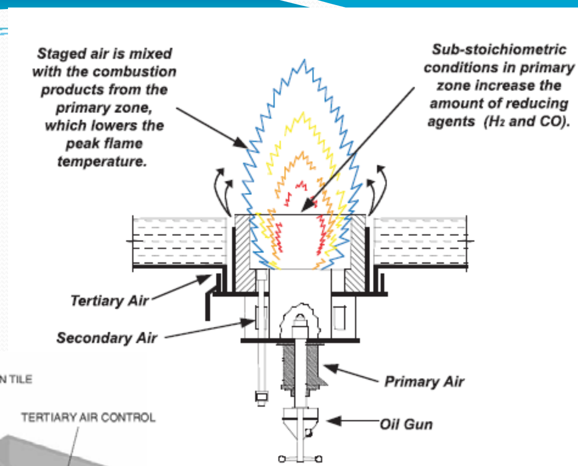
- 1. Dasar-dasar Teknik Pembakaran (150')
- 2. Konsep Fundamental Kimia Sistem Pembakaran (2x150')
- 3. Konsep Perpindahan Panas dalam Sistem pembakaran (150')
- 4. Flame Impingement (150')
- 5. Perancangan Sistem Burner (2x150')
- 6. Troubleshooting Sistem Pembakaran (150')
- 7. Bahan Bakar untuk Proses Pembakaran (2x150')
- 8. Permodelan Proses Pembakaran (2x150')
- 9. Pengendalian Proses Pembakaran (150')
- 10. Keselamatan Proses Dalam Sistem Pembakaran (2x150')
- 11. Sistem Flare di Teknologi Pembakaran (150')

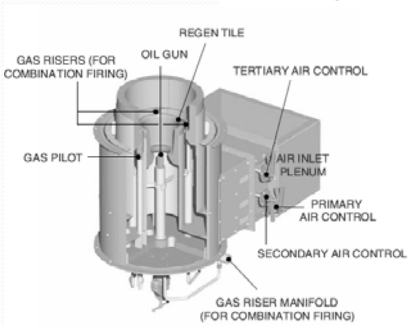
FLAME FROM COMBUSTION PROCESS

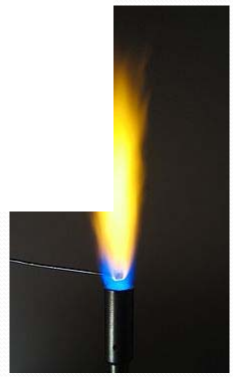
- Most previous research has concerned **air/fuel combustion** ➔ lower intensity flames ➔ the predominant mechanism is forced convection.
- Much work has also concerned **fuels combusted with pure oxygen** ➔ high-intensity flames ➔ produce significant amounts of dissociated species (e.g., H, O, OH, etc.) and uncombusted fuel (e.g., CO, H2, etc.).
- These reactive gases then impact on a relatively low-temperature target surface.
- As these species cool, they exothermically combine into products such as CO2 and H2O, which are more thermodynamically stable at lower temperatures

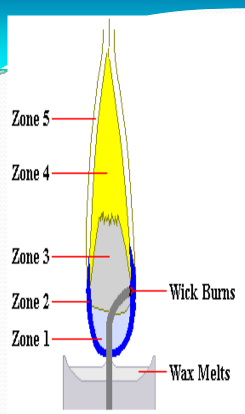
Basic Flame Type

Fuel/Oxidizer Mixing	Fluid Motion	Examples
premixed	turbulent	spark-ignited gasoline engine low NO_x stationary gas turbine
	laminar	flat flame Bunsen flame (followed by a nonpremixed candle for $\Phi > 1$)
nonpremixed	turbulent	pulverized coal combustion aircraft turbine Diesel engine H_2/O_2 rocket motor
	laminar	wood fire radiant burners for heating candle



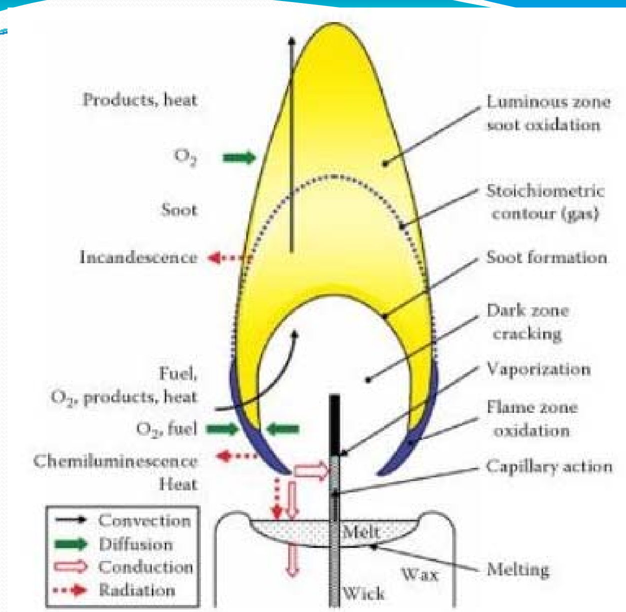






CANDLE FLAME ZONES

- **Zone 1 (Non-Luminous Zone)** - Fuel on the wick evaporates. There is insufficient oxygen for fuel to burn. Temperature is about 600 C near the wick.
- **Zone 2 (Blue Zone)** - There is a surplus of oxygen and the flame burns clean and blue. Temperature is around 800 C.
- **Zone 3 (Dark Zone)** - Pyrolysis (cracking) of the fuel begins due to the shortage of oxygen creating minute carbon particles. The temperature is about 1,000°C.
- **Zone 4 (Luminous Zone)** - This area is bright yellow. There is still insufficient oxygen for complete burning so pyrolysis continues and larger carbon particles are produced. The temperature is around 1,200°C.
- **Zone 5 (Veil)** - There is oxygen surplus in this non-luminous zone and carbon particles burn faster and more completely at the boundary between Zone 4 and Zone 5. The temperature is around 1,400°C.



Flame Temperature from some fuels

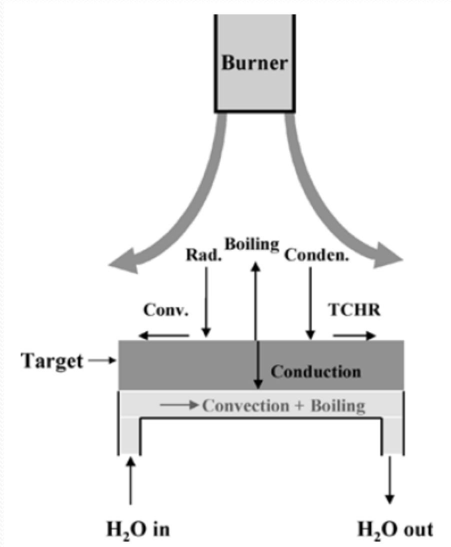
Material burned	Flame temperature (C)
Charcoal fire	750–1,200
Methane (natural gas)	900–1,500
Propane blowtorch	1,200–1,700
Candle flame	~1,100 (majority), hot spots may be 1300–1400
Magnesium	1,900–2,300
Hydrogen torch	Up to ~2,000
Acetylene blowlamp/blowtorch	Up to ~2,300
Oxyacetylene	Up to ~3,300
Back draft flame peak	1,700–1,950
Bunsen burner flame	900–1,600 (depending on the air valve)

Material burned	Max. flame temperature (C, in air, diffusion flame)
Wood	1027
Gasoline	1026
Methanol	1200
Kerosene	990
Animal fat	800–900
Charcoal (forced draft)	1390

Heat Transfer Mechanism in Flame Impingement

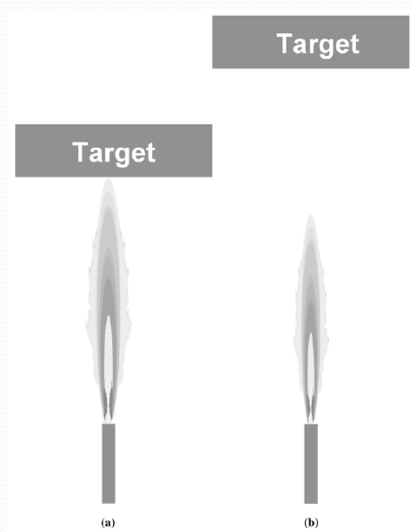
- Six heat transfer mechanisms have been identified in previous flame impingement studies:
  - convection (forced and natural),
  - conduction (steady-state and transient),
  - radiation (surface, luminous, and nonluminous),
  - thermochemical heat release (equilibrium, catalytic, and mixed),
  - Water vapor condensation,
  - and boiling (internal and external
- All of the mechanisms are not usually present simultaneously and depend on the specific problem.
- ===> Heat transfer mechanisms in flame impingement on **a water-cooled target**

Heat transfer mechanisms in flame impingement on a water-cooled target



Schematic of forced (a) and natural (b) convection in flame impingement

- In **natural convection flame impingement**, the flame is often far from the surface
- so that the buoyant hot combustion products blended with cooler ambient air are impinging on the target.



Radiant Heat Transfer In Flame Impingement For Luminous Flames, Nonluminous Flames And Surface Radiation From Hot Furnace Walls

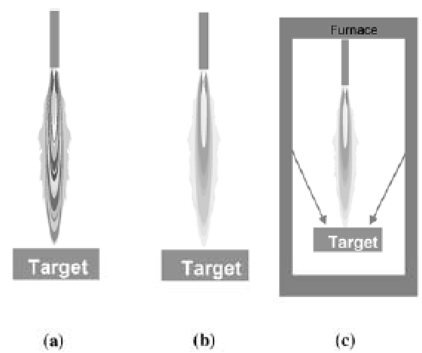
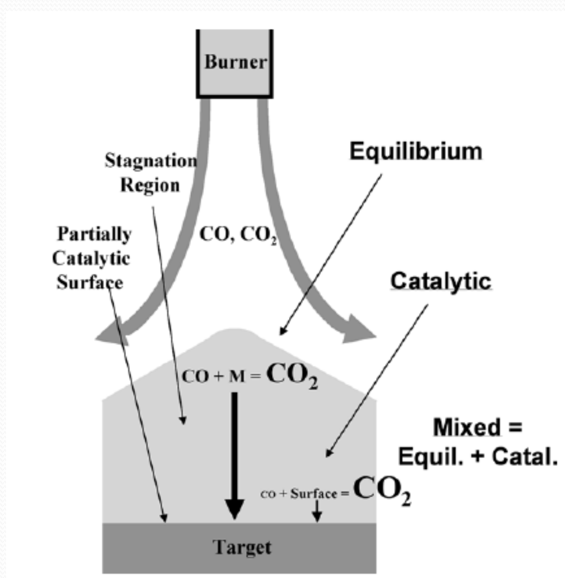


FIGURE 7.5 Radiation heat transfer mechanisms in flame impingement: (a) luminous flame, (b) nonluminous flame, and (c) surface radiation.

Thermochemical heat release mechanisms in flame impingement



Important Parameters Arise In Flame Jet Impingement Processes

- The first and most important aspect is the overall **geometric configuration** ➔ includes the target shape and its orientation relative to the burner.
- These operating conditions strongly influence the **heat transfer intensity**.
- They also determine which mechanisms will be most important.
- These conditions include: **the oxidizer composition**, the **fuel composition**, the **equivalence ratio**, and the **Reynolds number at the nozzle**

Other factors commonly have secondary influences on the heat transfer processes

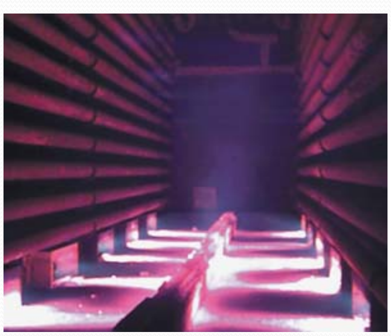
- the burner design and the position relative to the target.
- The characteristics of the target also influence the heat transfer.
- These include: the **dimensions**, **material composition**, **surface treatments or coatings**, and the **surface temperature**.

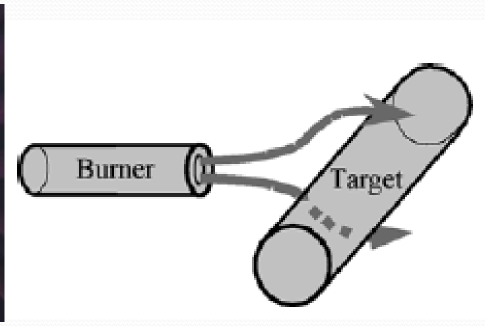
The Four Most Common Geometric Configurations In Flame Jet Experiments Have Been Flames Impinging

- (1) normal to a cylinder in crossflow,
- (2) normal to a hemi-nosed cylinder,
- (3) normal to a plane surface,
- (4) parallel to a plane surface

(1) Flame Normal to a Cylinder in Crossflow

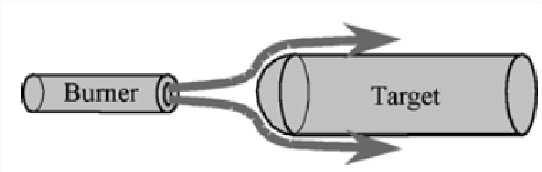
- The average heat flux over the entire surface was calculated from the sensible energy gain of the cooling water

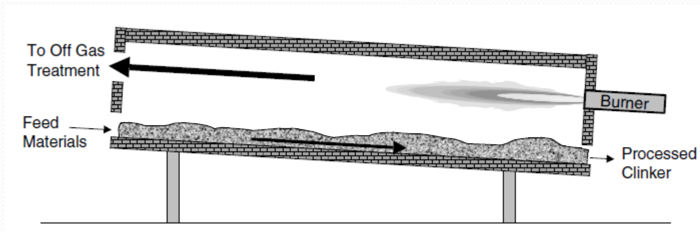




(2) Flame Normal to a Hemispherically Nosed Cylindrical

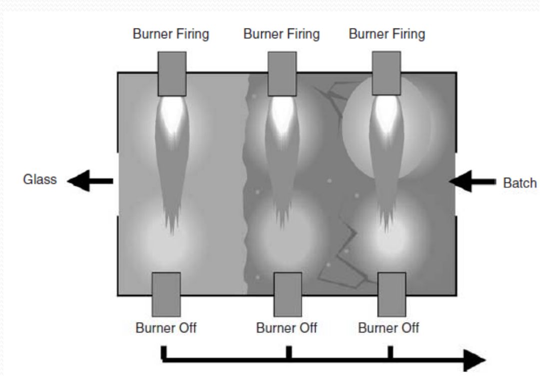
- The flame impinges on the end of the cylinder, which is hemispherical.
- These tests have been very important in aerospace applications.
- This relatively uncommon geometry for industrial application

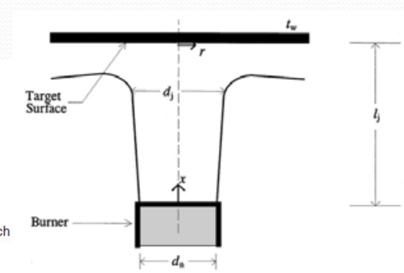




(3) Flame Normal to a Plane Surface

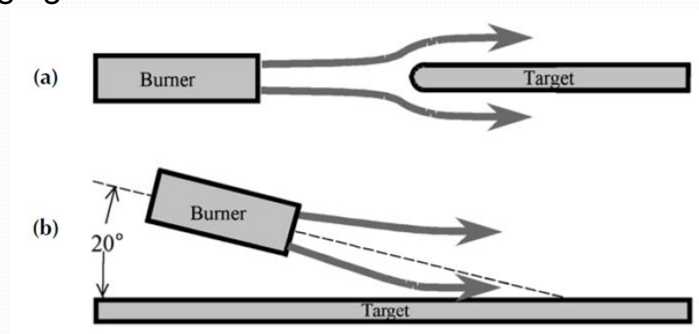
- This configuration has received the most attention since it has been widely used in many industrial processes





(4) Flame Parallel to a Plane Surface

- It is very important for flight applications
- This type of flame promises to give more uniform heating of the surface, compared to flames impinging normal to a surface



OPERATING CONDITIONS

- Operating conditions have been found to **strongly influence the heat transfer intensity**.
- The effects include:
  - the oxidizer
  - fuel composition,
  - flame equivalence ratio
  - firing rate,
  - Reynolds number at the nozzle exit,
  - burner type,
  - nozzle diameter,
  - location of the target with respect to the burner

Oxidizers Composition

- The most important variable, after the physical configuration, is the **oxidizer composition**
- The oxygen mole fraction in the oxidizer, Ω, has a very large influence on heat transfer intensity.
- Almost all previous studies used either air (Ω = 0.21) or pure oxygen (Ω = 1.0) as the oxidizer
- This **affects both the flame temperature and the amount of dissociation** in the combustion products.

Fuels Composition

- **Natural gas and methane** (the main constituent in natural gas) have been the most widely used
- The combination of **fuel type** and the **equivalence ratio** Φ determines the tendency to produce soot and, therefore, luminous gas radiant emission.
- This tendency is higher in fuel-rich mixtures (Φ > 1).
- It also increases with higher carbon-to-hydrogen weight ratios in the fuel.
- For example, C_4H_{10}, which has a C:H weight ratio of 4.8, has a higher propensity to produce soot than CH_4, which has a C:H weight ratio of 3.

Equivalence Ratios (ϕ)

- **Φ, is a fuel:air ratio** ; This ratio directly affects both the sooting tendency and the level of dissociation in the combustion products.
- **Fuel-rich flames (Φ > 1)** produce a combination of both luminous and nonluminous thermal radiation.
- The combustion products of these flames may also contain unreacted fuel components, due to insufficient oxygen.
- **Fuel-lean flames (Φ < 1)** normally do not produce luminous thermal radiation, due to the absence of soot particles.
- These flames seldom produce significant quantities of unreacted fuel species unless the flame temperature is high enough to produce dissociation.
- **Flames at or near stoichiometric (Φ = 1)** produce the highest flame temperatures

Firing Rates

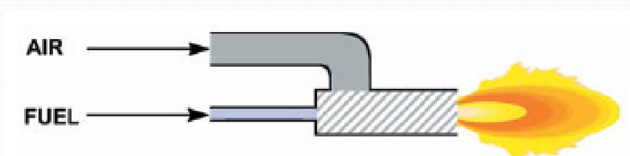
- The **firing rate** or **gross heat release** of the flames has ranged from 0.3 to 3000 kW (103 to 107 Btu/hr).
- In the other three studies, the flames impinged on water-cooled targets located inside a furnace environment.
- Many of the studies considered here used torch tips, firing at under 50 kW (170,000 Btu/hr).

Reynolds Number

- The **Reynolds number at the burner nozzle**, Re_n, varied from 50 to 330,000.
- Both laminar and turbulent flow conditions arose.
- For some studies, the flows were indicated to be either **laminar or turbulent**.
- In other studies, the **nozzle Reynolds number** was estimated from other information, such as nozzle diameter and gas flow rates.
- The Reynolds number varies directly with the burner diameter. It is also influenced by burner design.
- In partially or fully premixed flames, the combustion products leave the burner at an elevated temperature. However, in diffusion flames, the gases leave the burner at essentially ambient conditions.
- Since the gas viscosity increases with temperature, Re_n is generally lower if the gases have been heated at the burner exit.

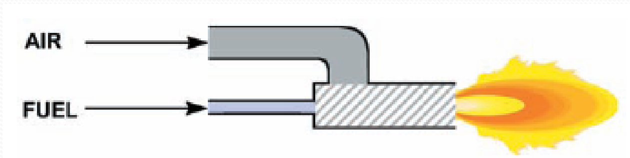
Burners Type

- Many different types of burners have been used. These range from fully premixed to diffusion mixing, downstream of the burner exit.
- In **fully premixed burners**, **the fuel and oxidizer mix prior to reaching the nozzle exit**
- The premixed gases were fired in a burner consisting of a tube with a stainless steel mesh
- The resulting flame in premixed burners may have either a uniform or a nonuniform velocity profile, depending on the nozzle design.
- It also depends on the distance between the ignition point and the exit.



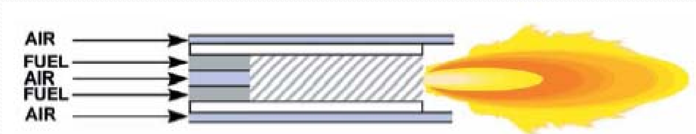
Fully Premixed Burner

- The **tunnel burner** is a common **fully premixed burner**.
- The **gases are mixed and ignited inside the burner**.
- They then travel through a refractory-lined chamber before leaving the burner.
- The combustion products may equilibrate inside the chamber.
- The temperature and composition are then uniform at the exit. However, the velocity profile may not be uniform.



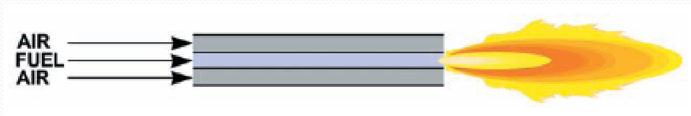
Partially Premixed Burners

- In **partially premixed burners**, the fuel and oxidizer mix prior to reaching the nozzle exit.
- However, **only a portion of the stoichiometric amount of oxygen is supplied through the burner**.
- The rest is provided by mixing with the surrounding ambient air, entrained into the flame.
- At the nozzle exit, the velocity profile is commonly nonuniform.
- Both uniform and nonuniform outlet temperature profiles and compositions have been reported



Diffusion-Mixing Burners

- In **diffusion-mixing burners**, **the fuel and oxidizer begin to mix at the nozzle exit** , where the velocity is often nonuniform.
- In diffusion burners, the exit temperature field is commonly homogeneous and equal to ambient conditions.
- The gas composition at the exit is pure fuel and pure oxidizer, with no combustion products.
- If the oxidizer is not supplied through the burner, a pure diffusion flame results.
- The oxygen is provided for combustion by ambient air entrainment into the flame.



Location of Burner to the Target

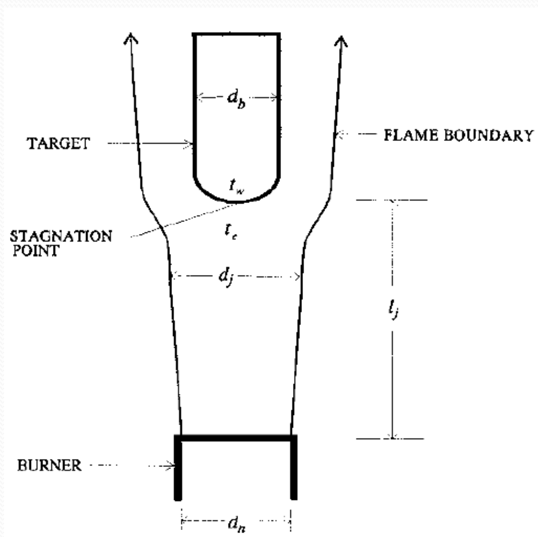
- Distance between burner to the target has a strong influence on the resulting heat transfer to the target. **Shorter distances result in higher flux rates**.
- One cause **is less ambient air entrainment**. Another reason is that **the flame widens at longer distances**. This diffuses the heat flux over a wider cross-sectional area.
- **The location varied with the oxidizer composition and the equivalence ratio.**
- The radiation from the hot refractory walls to the target is a significant portion of the total heat flux to the target

Flame Jet Impingement Studies with the Target in a Furnace

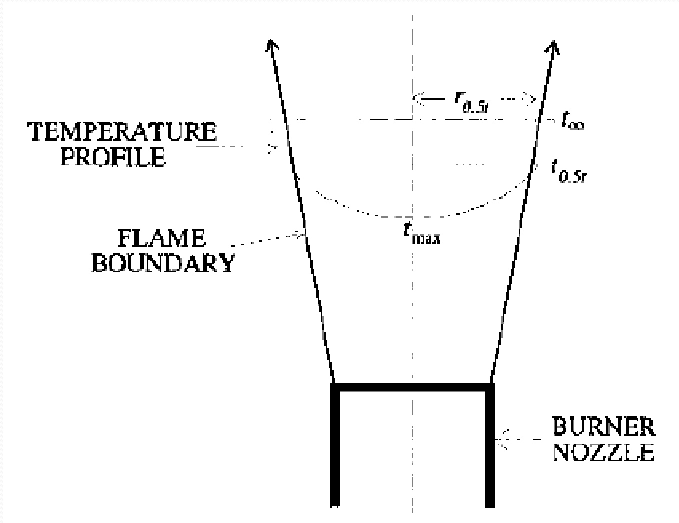
Ref.	Furnace Wall Temp. (K)	Furnace Dimensions (m)
Beér and Chigier, 1968[23]	1200–1500	2 W × 2 H × 6.25 L
Vizioz and Lowes, 1971[25]	Not given	2 W × 2 H × 6.25 L
Smith and Lowes, 1974[37]	Not given	2 W × 2 H × 6.25 L
Matsuo et al., 1978[30]	1300–1500	2.16 W × 1.80 H × 1.36 L
Rajani et al., 1978[38]	770–1870	1.0 dia. × 4.5 L
Ivernel and Vernotte, 1979[28]	1650–2000	0.6 dia. × 2.05 L

Source: From C.E. Baukal and B. Gebhart, *Comb. Sci. Tech.*, 104, 339-357, 1995.

Flame impingement on a hemi-nosed cylinder



Gas temperature profiles in a flame jet



For calculation detail of flame:

- C. E. Baukal, 2000, HEAT TRANSFER IN INDUSTRIAL COMBUSTION, CRC Press, Florida, Chapter: 7