AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

HEAT TRANSFER FROM IMPINGEMENT INVERSED DIFFUSION FLAME ON A HORIZONTAL FLAT PLATE

By

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A Thesis Submitted In Accordance With the Requirements
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ABSTRACT

Analysis of the nature of the inverse diffusion flame, IDF, and the performance of the IDF burners supported by an extensive experimental work using LPG was undertaken to investigate the influence of both of the geometric parameters of the inversed diffusion flame port array burners and the jet dynamics on the produced flame characteristics. The port array burner geometric parameters of the IDF are the central air flow area, the fuel jets flow area, the number of the fuel jets and the radius of the pitch circle around which the fuel ports are arranged. The jet dynamics are the air and the fuel flow rates and their momentum flux. Assessment of the performance of such burners and the type of flame they produce ought to take into consideration the dual interactions of these parameters.

An experimental work was carried out to investigate the influence of both of the burner geometry and the air and the fuel jets dynamics on inverse diffusion flame characteristics. In this regard the effect of varying the air as well as the fuel jet momentum flux of inverse diffusion burners of the circumpherntially arranged fuel jet ports (CAP) on the rate of mixing of the air and fuel and consequently on the flame characteristics, emission and heat transfer rate at different equivalence ratios were examined.

The variation of the momentum flux of the air took place by increasing the air flow rate, while its single central port diameter was unchanged during all of this work. The fuel jets velocity during these experiments was very nearly constant,

while the jets Reynolds number varied within a narrow range due to the variation of the fuel jets outlet ports diameters as their number was increased.

Nine IDF burners with different fuel jet ports 2, 1.4, and 1.1 mm, were designed with different pitch circle radii (P), which are the distance between the air port center and the corresponding fuel ports center, 10, 15 and 20 mm. The corresponding pitch circle diameters are 20, 30, and 40mm. The fuel ports diameters allow the same flow velocity in all burners if the mass flow rate was the same. The central air jet port in all of them is 6mm. These arrangements of the fuel ports enabled the investigation of the influence of increasing the number of the fuel air ports and the pitch circle radius. The fuel flow rate was kept constant while the air flow rate was varied to cover a wide range of the central air Reynolds numbers and a corresponding range of the primary equivalence ratio.

The experiments carried out in the investigation of the IDF in this work, are divided into four phases. The first part is concerned with the nature of the inversed diffusion flame jets, their influence on the development of two zones of combustible fuel-air mixtures, the formation of two flame fronts and the determination of the physics of the produced flames either necked inversed diffusion flames, normal diffusion ones or a combination of them and the rate of ambient air entrainment. The second part is concerned with the investigation of the visual characteristics of the IDF produced by these burners, including the flame stability limits, the flame appearance, its height and shape. The third part is concerned with some of the internal characteristics of the flame, the local overall equivalence ratio and emissions. The fourth phase is concerned with the thermal characteristics, the temperatures and the impingement heat transfer measurements.

The analysis of the nature of the jet dynamics revealed that two flame fronts are formed in the entrainment zone of the inversed diffusion flame, one of them in the co-flowing jet formed by the fuel and the central air jet and the other is in the peripheral submerged jet formed by the fuel jets and the ambient air. Beyond the neck the central air jet, the fuel jets and the two flame fronts merge and flow upward as one flame torch.

The results of the experimental work showed that at the high air jet Reynolds number 10466 to 9397 and low fuel Reynolds number 377 to 218, corresponding to the primary equivalence ratio near unity, the inverse diffusion flames produced by the burner of the lower pitch circle radius 10mm are short, blue color and sootless. On the other hand, a change of the flame color from being bluish when using the burners of the smaller pitch circle radius (P=10mm) to a yellowish color for the burners that have large Pitch circle radius (P=20mm) took place for all burners at the same values of the air Reynolds number and the fuel Reynolds number. At the low fuel Reynolds number of 377 to 218 when the air Reynolds number was gradually decreased to a low value 2081 corresponding to a primary equivalence ratio, Φ_p=4.5, the flame from all the burners was normal diffusion yellow very sooty one.

As the fuel flow rate and the corresponding fuel Reynolds number increased to four times, its momentum flux increased 16 times that encountered in the other experiments and the primary equivalence ratio increased to 8.04 while the air Reynolds number was 4072, the flame became a combination of the neckless normal diffusion flame having the two flame fronts and a cold air core as those of the inversed diffusion flames.

The results obtained using burners having different numbers of fuel ports while keeping the fuel mass flow constant revealed that the number of the fuel ports influences the characteristics of the flame.

The flame became more bluish and shorter as the number of the fuel ports increases. The flames obtained at a low air Reynolds number corresponding to primary equivalence ratios up to 4 by the burner which have the lowest number of ports, 12, were yellow and sooty, while the flames produced by the burners that have larger number of the fuel ports are less sooty and tend towards completion of combustion. The flames produced by all these burners at primary equivalence ratios up to 4 showed the formation of an inverse-bowel-shaped base ending with a neck in which the entrainment of the fuel towards the air jets are completed.

The results indicated that the entrained air has an important role in completion of the combustion for primary air ratios higher than unity. It was found that the amount of the entrained ambient air at the end of the flame is several times that provided by the central air port and it is responsible for the radial temperature drop at the large flame heights. In

these experiments, when the number of the fuel ports was increased while keeping the mass flow rate and the fuel exit velocity constants, the amount of the entrained air obtained at the end of the flame decreased.
The results proved that the nature of the flames from port array burners whether being inverse diffusion flame, normal diffusion flame or a combination of them is determined by the combined effect of the parameters of both of the burner geometry and the jet dynamics. The air Reynolds number and the primary equivalence ratio, Φ_p, may be used to describe the performance of a particular burner of invariable geometric parameters. Also the performance of a burner under any conditions of its air Reynolds number and primary equivalence ratio cannot be used to predict the performance of another different burner unless the conditions of geometric and dynamic similarities are satisfied.

At the small pitch circle distance (P=10mm), the centerline temperature profile shows higher temperatures. The center line temperature increases also with the increases of the number of fuel jets for all values of the primary equivalence ratio, although it is associated with a decreased fuel jet Reynolds number.

On the other hand, the higher burning rate of the fuel at the small pitch circle distance, P=10mm, with the higher number of the fuel jets, which produces a blue color flame and high flame temperature distribution is associated with favorable low CO and NOx levels.

It is observed that as the fuel lean mixture conditions are approached, the flame heat flux distribution at any flame height decreases with increasing the air jet Reynolds number Re_{air} by increasing the primary air flow rate. This increase of the primary air flow rate is accompanied by a decrease in the primary equivalence ratio (Φ_p) and an increase of the entrained ambient air. The increase of the supplied as well as the entrained ambient air causes lower flame jet temperatures. The results showed also that the IDF burners with small pitch circle distance and high number of the fuel jets produce high heat flux distribution along the flame length.

NOMENCLATURES

A/F	:	The air to fuel ratio
A_j	:	The thermocouple junction heat transfer area, (m^2).
$d_{air,}$ d_a	:	The air port diameter, mm
$d_{fuel,}$ d_f	:	The fuel port diameter, mm
E_{th}	:	The emission power of the ambient
EI	:	The emission index
h_c	:	The convective heat transfer coefficient, W/(m^2 ^oC).
m_i	:	mass of species i
m^0	:	The mass flow rate of the fluid
N_f	:	The number of the fuel ports
Nu	:	Nusselt number.
P	:	Pitch circle distance, mm.
p	:	The stagnant ambient air pressure away from the jets
Pr	:	Prandtl number
p_∞	:	The stagnant pressure of the entrained air at the fuel jet emergence
Δp	:	The pressure drop
$Q_{Rf\rightarrow j}$	:	The heat transfer rate from the flame to the thermocouple hot junction by radiation.
$Q_{convection\ f\rightarrow j}$	:	The heat transfer rate from the flame to the thermocouple hot junction by convection.
$Q_{R\ j\rightarrow a}$	:	The heat transfer rate from the hot junction to the surrounding.
q”	:	The heat flux (in W/cm^2)
R	:	The radial distance, mm
Re_{air}	:	Air jet Reynolds number, dimensionless, $(\rho_{air}.v_{air}.d_{air})/\mu_{air}$.
Re_{fuel}	:	Fuel jet Reynolds number, dimensionless, $(\rho_f.v_f.d_f)/\mu_f$.
Ta	:	the ambient temperature
T_f	:	Flame temperature, K.
T_{th}	:	Thermocouple junction (uncorrected) temperature, (K)
V_{air}	:	The air velocity, m/s
V_{fuel}	:	The fuel velocity, m/s
x_a	:	Air Concentration
x_f	:	Fuel Concentration
Z	:	Vertical flame distance measured from burner tip, cm.
α_f	:	The flame absorptivity at the ambient temperature
$\alpha_{th,a}$	:	The thermocouple absorptivity at the ambient temperature

$\alpha_{th,f}$	:	The thermocouple absorptivity at the flame temperature
σ	:	Stefan-Boltzmann constant, (5.67E-8 $W/m^2.K^4$)
Φ	:	The equivalence ratio, dimensionless which is the ratio between the stoichiometric air to fuel ratio to the actual air to fuel ratio, ($\Phi = \frac{(A/F)_{stoic}}{(A/F)_{Actual}}$).
Φ_p	:	Primary equivalence ratio, dimensionless which is the ratio between the stoichiometric air to fuel ratio to the actual primary, (the central air jet), air to fuel ratio.
Φ_o	:	Overall equivalence ratio, dimensionless which is the ratio between the stoichiometric air to fuel ratio to the summation of the central air jet plus the flow rate of the entrained ambient air to fuel ratio.
ρ_{air}	:	Air Density, Kg/m^3.
ρ_{fuel}	:	Fuel Density, Kg/m^3.
ε_{th}	:	The emissivity of the thermocouple bead.
ε_f	:	The flame emissivity.
μ_{air}	:	The air dynamic viscosity, Pa.s.
μ_{fuel}	:	The Fuel dynamic viscosity, Pa.s.

ABBREVIATION

NDF	:	Normal diffusion flame
IDF	:	Inversed diffusion flame
CAP	:	Circumferential arranged fuel port
CoA	:	Co-axial
HFS	:	heat flux sensor
RTS	:	resistance temperature sensing element

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