AN ANALYSIS ON MICROWAVE PLASMA FLAME POWER SUSTAINABILITY: TEMPERATURE GRADIENT – THERMAL SPEED – FLAME GROWTH SPEED

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Abstract. *The generation and behavior of microwave plasma flame in a gasification reactor (MCw GASIFIER) is analyzed. Microwave plasma generation is at a frequency of 2450 MHz at atmospheric pressure. Air at the rates of 50 L/min and 100 L/min are used in the power (P) range of 3000 W ≤ P ≤ 6000 W. Local instantaneous temperature T=T (y,t) measurements along the flame (y) are referred. The time-averaged temperature (Ty) is calculated from the instantaneous data T (t). The power sustainability of flame is estimated through defined parameters of temperature gradient (TG), thermal speed (VT) and flame growth speed (Vy). TG =dT y /dy is a measure of flame thermal growth. VT=ΔTy /Δt indicates the local time averaged temperature gradient (ΔTy during the time (Δt) for the increase of power (ΔP). Vy =VT/TG is the derived parameter. The existence of a linear relationship between Vy and VT for 50 L/min air flow is the confirmation of the modeling, sensitivity of flame generation and accuracy of the temperature measurements.*

Keywords: *Microwave Plasma Flame, Plasma Power, Flame Temperature Gradient, Flame Thermal Speed, Flame Growth Speed*

1. Introduction

It is known that ignition chemistry and its influence on combustion has a coupling with a dramatic problem of misfiring and failed ignition [1]. In order to solve this problem; microwave enhancement is used as an advanced ignition technology. The ignition delay associated with reaction kinetics can be reduced by means of high concentrations of radicals in plasma [2, 3]. Padalaet al. 2017 [4] have conducted a study upon flame size measurements in a premixed propane-air mixture at varying amounts of air by a microwave-enhanced plasma. They paid attention to the minimum size of flame, flame speed and sustainability of flame from an initial spark kernel to a propagating form.

Somehow a similar study with a different methodology under the influence of a wide range of parameters for the determination of microwave plasma flame power sustainability is the topic of the paper.

The generation and control of microwave plasma flame the estimated dimensional characteristics and flame temperature measurements are given briefly in a previous paper of the authors [5, 6]. The generated microwave plasma flame is in use for the decomposition of solid wastes in the gasification reactor of MCw GASIFIER [7]. However the focus herein is on the analysis of microwave plasma flame growth as a counterpart of study [4]. The analysis is founded on flame local instantaneous temperature measurements, T(y,t) along the plasma flame (y) under the influence of plasma environment gas rate and applied power (P). The generated flame is directed as a downflow jet leaving the complete assembly of plasma applicator with reactor head. Pure air in the closed gasification reactor at atmospheric conditions in the range of power (P); 3000 W ≤ P ≤ 6000 W is considered since air-steam mixtures cause reduction in the size of flame. The analysis is through the introduction of parameters for flame power sustainability. The defined parameters of TG, VT, Vy are given in comparison with Padala et al's approach [4].

2. Material and Methods

MCw GASIFIER [5, 6] is an open cycle blower type set-up using microwave plasma generation and control system of MUEGGE (Table 1). The system is able to generate microwave plasma at a varying input power up to a maximum power of 6000 W at a frequency of 2450 MHz with the air as the plasma environment gas. The increment of power is having a sensitivity of 1%.

The generation and control of power (P) is by means of the software program of MUEGGE MX model. The utilized power supplier is MUEGGE MX6000D-110 K.

Table 1. MCw GASIFIER System Description

SYSTEMS OF MCw GASIFIER	TYPE	SUB-SYSTEMS(COMPONENTS)	CHARACTERISTICS- FUNCTION	UTILIZED RANGE
MICROWAVE PLASMA GENERATION AND CONTROL SYSTEM	MUEGGE (SOFTWARE PROGRAM: Muegge MX model control software)	MX6000D-110K model power supplier MH6000S-213BF model magnetron head (In combination with Isolator, 3-D Stub-Tuner, Wave Guide Plasma Applicator)	Generation of Power up to P= 6000 W Generation, control and transmission of microwave signal to introduce plasma	3000 W ≤P≤ 6000 W Sensitivity: 1% variation in power (P) Frequency of 2450 MHz
	Elimko E-PR-110 model data acquisition card			
GASIFICATION REACTOR	Custom-made fixed bed, cylindrical, swirling inlet of plasma gas at reactor head	Reactor head (In combination with plasma applicator)	Height: 125 mm	
		Main body	Height: 500 mm Diameter: 81 mm	Local temperature measurements
PLASMA ENVIRONMENT FEEDING SYSTEM	Air Supplier: Lupamat LKV 30/8 model screw compressor.	Flow rate measurement: ALICAT MCR-250SLPM-D model mass flow controller is used	Compressed air which has maximum 8 bar pressure and 4850 L/min flow Uncertainty: 0.7 L/min	50 L/min Air pure 100 L/min Air pure

Air supplier is LUPAMAT LKV 30/8 model screw compressor in connection with ALICAT MCR-250SLPM-D model mass flow controller. Gasification reactor is a custom-made stainless steel cylindrical main body in combination with a reactor head and plasma applicator assembly having a length of 125 mm. Diameter of the reactor is 81 mm and a length of 500 mm.

The reference line is the edge of plasma applicator resulting in a total length of 625 mm of the reactor assembly. Plasma environment gas – air inlet is directed from the reactor head as a swirling jet. Plasma applicator is in combination with the reactor head. Quartz glass tube located at the center of plasma applicator-reactor head assembly has a diameter of 3 cm and length of 5 cm.

It is observed with the pictures of free- jet downflow plasma flame taken by a digital camera of SONY CYBERSHOT DSC-W220 12.1 that flame center is coincident with the axis of the quartz tube [5]. The recorded pictures were analyzed by using the digitizer tool of commercial ORIGIN PRO 8.5.1 software program. Although pointed end- conical and spreading shapes are observed; the shape of flame can be approximated as a cylinder. In the covered P≥ 3000 W, flame has a length (L) which is parallel to y; L ≥ 25 cm and a diameter (D) perpendicular to y; D ≥ 3.5 cm. A sample flame photograph is given in Fig. 1.

The generated microwave plasma flame was directed in the closed reactor at varying operational conditions and temperature measurements along the flame were conducted. B type (Pt18Rh-Pt) thermocouples having the measurement range of temperature up to 1820℃ with a sensitivity of ±4 ℃ were used. Thermocouples were located at 5 different locations of y= 175 mm, y= 275 mm, y= 375 mm, y= 475 mm and y= 575 mm along the reactor wall. Thermocouple probes were immersed at 4 cm from the reactor wall such that probe tips were 0.5 cm apart from the reactor centerline. Based on the visual treatment of plasma flame and the dimensions determined it was seen that the thermocouple probe tips were inside the flame cross- section in the invisible reactor. The first two thermocouples were inside the main flame body while the others were in the effective tail region of the flame inside the closed reactor.

Fig. 1. Plasma flame as a downflow free jet in open atmosphere at 50 L/min air with P=3600 W

The sketches of the reactor in the operational mode of gasification process are given in Fig. 2. The temperature measurements given in the paper are for the downdraft case of the reactor with reverse of the described case in Fig. 2 (reactor head and plasma applicator are on the top of reactor and flame is directed as a downflow jet).

The temperature measurements were taken at 1 second intervals and the data were stored in ELIMKO E-PR-110 model data acquisition card installed in a PC. Time averaging of the collected local instantaneous temperature data T=T(t) were used to determine the local time- averaged flame temperature, Ty as follows:

$$Ty = \frac{1}{N}\sum_{t=1}^{N} T_{(t)} \quad (1)$$

Where N: number of thermocouple data

N is used as 300 and 1200 corresponding to the 5 min and 20 min operational time respectively.

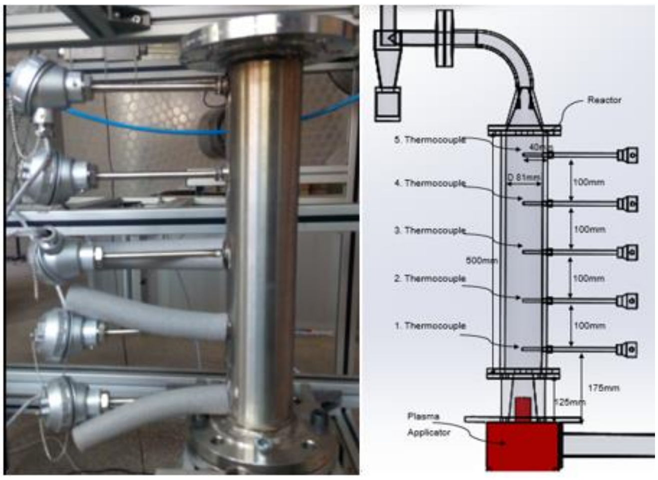

Fig. 2. Reactor with thermocouple positions in the operational mode of updraft gasification case

3. Results and Discussion

3.1 The comparison of the utilized approach with the one of Padalaet al. 2017 [4]. The comparison of the utilized approach is given with the one of Padala et al., 2017 specified in Table 2. They used Schlieren Diagnostic System inside a closed chamber having 185 cm3 volume. Spark ignition, SI followed by microwave enhancement is the case they considered. Their frequency is also the same as our study with 2450 MHz.

Table 2. Specifications of the study of Padala et al., 2017

INPUT POWER	TYPE AND AMOUNT OF FLOW RATE	EXPERIMENTAL CONDITIONS	SIZE OF FLAME
P = 500 W	Propane-Air Mixture at varying equivalence ratios up to 0.7	-Closed chamber 185 cm^3 -SI Followed by Microwave enhancement -At a pressure of 120 kPa Measurement means -Schlieren diagnostic system	Data at an equivalence ratio of 1 varying between D= 0.5 cm - 2 cm Data at a varying equivalence ratio varying between D= 0.5cm- 1 cm Data at an equivalence ratio of 0.7 varying between D= 0.5 cm- 2 cm Data at a dry air varying between *L= 0.2 cm- 0.6 cm*

Propane-Air mixture at varying equivalence ratios of up to 0.7, equivalence ratio 1 and dry air data are referred at a constant input power of P= 500 W. The listed differences are as follows:

1. The volume of the chamber is 1/13.92 of the present study reactor
2. The pressure is 120 kPa for their study while in the presented study standard atmospheric pressure is used.
3. In the present study an extensive range of power (P), is taken into account to estimate the major influence of power (P) on the generated flame.
4. Their estimated shape of flame is spherical - elliptical with their reference of a single size for flame. This size is corresponding to the length of flame (L) in the present study.
5. Their main purpose is to determine the influence of microwave plasma enhancement in comparison with spark ignition only. They determined flame size and flame speed under the influence of the equivalence ratio primarily

They concluded that the application of microwave plasma enhanced the flame characteristics.

In reference to Table 2 Padalaet al. 2017 [4]'s range of the estimated spherical-elliptical flame size (D) is between 0.2 cm -2 cm which are much less than the ones estimated from downflow free jet plasma flame of cylindrical shape. In case of the same P=500 W measurements of the referred study [5] diameter (D) is between 1.2 cm – 1.5 cm and length (L) is approximately 6 cm leaving the plasma applicator (of length 5 cm and diameter 3 cm) The reason is due to the methodology used and the case discussed.

However the determined flame speed of Padalaet al. 2017 [4] is the reference basis for the analysis of this paper. The magnitude of flame speed they measured can be approximated as 50 cm/s covering the flame size range of 1 cm < D < 2 cm for an equivalence ratio of 0.7. They also noticed the change in the shape –size of plasma kernel with the change in microwave pulse of a variable duration used between 0.1 ms and 1.5 ms. They also noted the difficulty of the differentiation between hot gas and pure plasma in their approach.

3.2 Flame generation as a function of power: used methodology. The generation of flame and therefore flame growth is governed by the magnitude of power (P). The flame generation in the closed invisible reactor is sensed by means of the measurements of thermocouples; T(y,t). The thermocouples' recording is a timely procedure as described by Eq. 1. In other words, thermal characterization of the flame is done instantly.

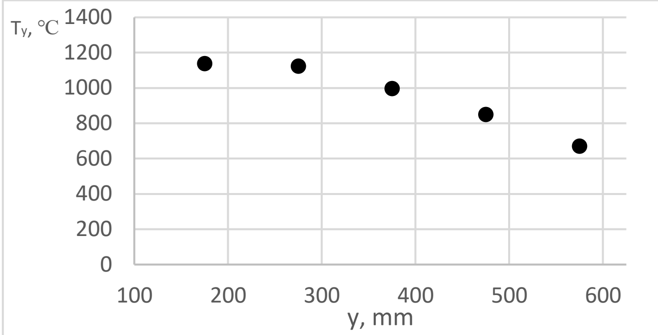

Figure 3a. Variation of Ty along flame for P= 5400 W at 50 L/min air

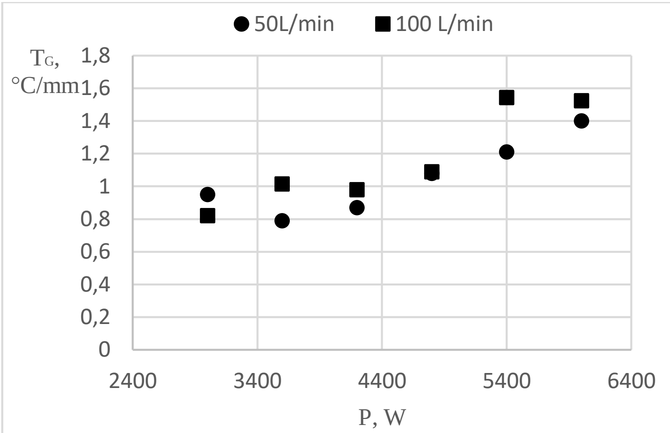

Figure 3b. Variation of TG magnitude with power (P) for 50 L/min and 100 L/min air flow rate

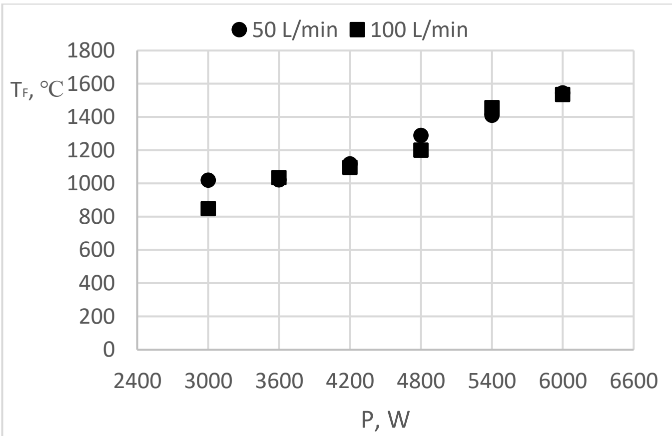

Figure 3c. T_F variation with power (P) for 50 L/min and 100 L/min air flow rate

The generation of the plasma flame with air at the rates of 50 L/min and 100 L/min at the start of the procedure for the lowest power application of P = 3000 W has an operation time of 20-minute time interval. The temperature data at each power (P) increment for P>3000 W is through 5-minute time intervals for the execution of the process. The input power is increased during the procedure covering the range 3000 W≤ P ≤ 6000 W at 600 W intervals (taking the intermediate levels of 3600W, 4200W, 4800W, 5400W). The sample data for the variation of Ty along the flame is given for P= 5400 W at 50 L/min rate of air in Fig. 3. The magnitude of Ty has a decrease along the flame with y; for all power (P).

As can be seen from sample plot in Fig. 3.a, Ty along flame has a linear change with y such that as y increases Ty decreases. The fitted equations have the following form:

$$\mathrm{Ty} = \mathrm{TG}\,\mathrm{y} + \mathrm{T_F} \qquad (2)$$

Where Ty in °C and y in mm. TG and TF are the constants with units °C/ mm and °C respectively defined as follows:

$$\mathrm{TG} = \mathrm{dTy}/\mathrm{dy} \qquad (2.a)$$

$$\mathrm{T_F} = (\mathrm{Ty})_{\mathrm{y}=0} \qquad (2.b)$$

TG is defined as the temperature gradient and TF is defined as the flame temperature at y=0. The deviation of experimental data from the estimated Eq. 2 is between the order of magnitude of ± 2 % and ± 21 % in the covered cases. Increased air rate results in a decrease in data scattering. The maximum data scattering is observed at the first two positions y=175 mm and y=275 mm since Ty almost stays constant for particularly P< 4200 W. The values of TG and TF are given in Table 3.

Table 3. TG and T_F values

FLOW RATE (L/min)	POWER (W)	TG (°C/mm)	T_F (°C)
50	3000	-0.95	1019,7
50	3600	-0.795	1022
50	4200	-0.866	1117,3
50	4800	-1.076	1289,9
50	5400	-1.212	1411,2
50	6000	-1.405	1545
100	3000	-0.82	848
100	3600	-1.014	1035
100	4200	-0.908	1096,4
100	4800	-1.085	1201,6
100	5400	-1.544	1456
100	6000	-1.524	1535,3

The ranges of the magnitudes are -0.795 ≤ TG ≤ -1.544 and 848≤ TF ≤1545 respectively (Fig.3b and Fig.3c). TF shows the temperature at the center of plasma applicator as the maximum magnitude of flame temperature. It seems that at $\mathrm{P} = 3000$ W, $\mathrm{T_F} = 1019$ °C at 50 L/min air; increase in power (P) to 6000 W causes an increase in $\mathrm{T_F} = 1545$ °C. For both power (P); at 100 L/min air the magnitudes of TF are less than the ones with 50 L/min. Variation of TG with power (P) for a given amount of flow rate have two conflictions for 50 L/min passing from $\mathrm{P} = 3000$ W to $\mathrm{P} = 3600$ W and for 100 L/min air passing from $\mathrm{P} = 3600$ W to $\mathrm{P} = 4200$ W with decreasing magnitudes of TG.

Meanwhile TF variation with power (P) can be described by the following Eq. 3 irrespective of the rate of air in an approximate error band of ± 5%

$$T_F = 0{,}2088\,P + 275{,}13 \qquad (3)$$

Where TF in units °C and P in W.

It means that irrespective of the rate of air increase in P causes increase in TF as an expected fact.

3.3 Modeling of microwave plasma flame: introduction of parameters. Power sustainability of flame can be expressed through the defined parameters of thermal speed (VT) and growth speed of flame (Vy) besides temperature gradient (TG). Temperature gradient (TG) of plasma flame is a function of power (P). A thermally stable flame generation is the case with the lowest magnitudes of TG. Thermal Speed, (VT) is defined as the change in Ty at a location, ΔTy with time Δt for increase in power (ΔP) and is expressed in units of ° C/s as defined in Eq. 4.

$$\mathrm{VT} = \Delta\mathrm{Ty}/\Delta\mathrm{t} \qquad (4.a)$$

Flame Growth Speed Vy is defined as the ratio of VT to TG and expressed in units of mm/s as follows:

$$\mathrm{Vy} = \mathrm{VT}/\mathrm{TG} \qquad (4.b)$$

The variation of VT with power (P) along the flame at different locations is given in Fig. 4.a and 4.b for 50 L/min and 100 L/min rates of air.

Plasma flame generation is such that 20-minute operation time was necessary for the initial temperature measurements at P= 3000 W since the reactor was at the temperature of the ambient. Therefore, the magnitudes of VT at all positions for P= 3000 W have their greatest magnitudes due to the case of the greatest magnitudes of ΔTy with the lowest magnitude of temperature in the reactor. The remaining temperature measurements were taken at equal 5 minute-operation time. It means that from P=3000 W to P= 6000 W total operation time is 25 minutes.

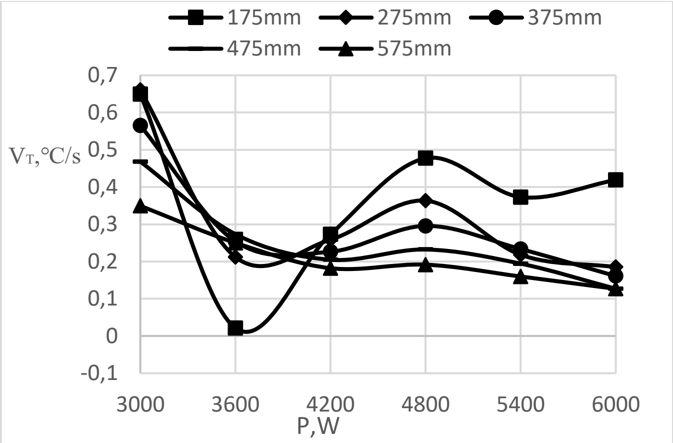

Fig. 4a. Variation of VT with power (P) at 50 L/min air

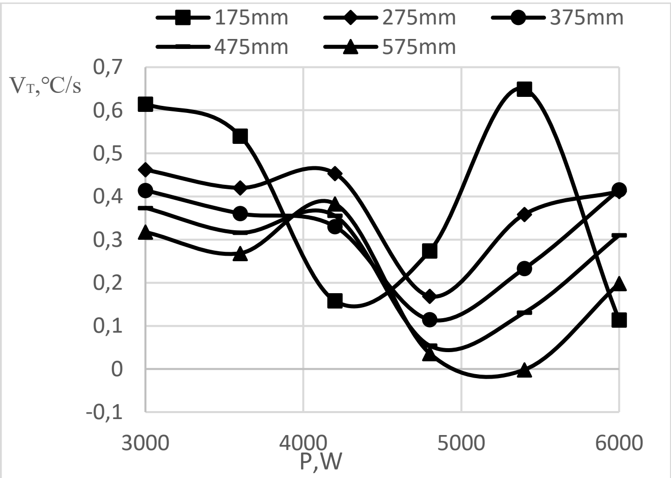

Fig. 4b.Variation of VT with power (P) at 100 L/min air

Therefore, the magnitude of VT is both dependent on location and applied power. The fluctuation behavior of VT with P at the first position, y= 175 mm is due to the generation of flame and the closeness of the location to the plasma applicator. The magnitude of VT varies with power (P) between 0.66 °C/s-0.0214 °C/s for 50 L/min air and between 0.6 °C/s-0.1 °C/s for 100 L/min air flow. Meanwhile for the other locations y>175 mm particularly for 50 L/min dependence of VT with power (P) over the covered range of P is smooth. The magnitudes of VT at all locations for the covered P are almost in the same order (P= 3600 W; VT= 0.2 °C/s-0.25 °C/s, P= 4800 W; VT= 0.19 °C/s-0.36 °C/s, P=6000 W VT= 0.13 °C/s-0.18 °C/s). It seems that increase in power (P) causes disappearing effect of location on VT. On the other hand, the behavior of VT with P for 100 L/min even for y>175 mm has a fluctuating variation different from the one observed in Fig. 4.a for 50 L/min air. Therefore, flame has shown a better thermal performance at the lowest rate of air.

In this respect for 50 L/min air the variation of VT with y at P=4800 W and P= 6000 W is given in Fig. 5.a for y>175 mm. It is seen that at P= 4800 W; VT varies between 0.36 °C/s to 0.19 °C/s from y= 275 mm to y= 575 mm while at P=6000 W the recorded values of VT are 0.18 °C/ s and 0.126 °C/ s.

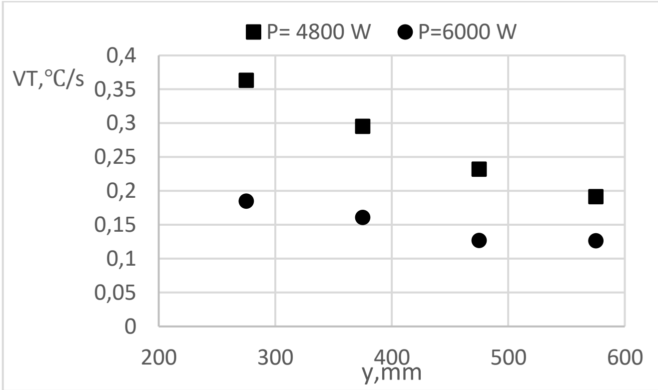

Fig. 5a. Variation of VT with distance along flame at different power (P) for 50 L/min air flow rate

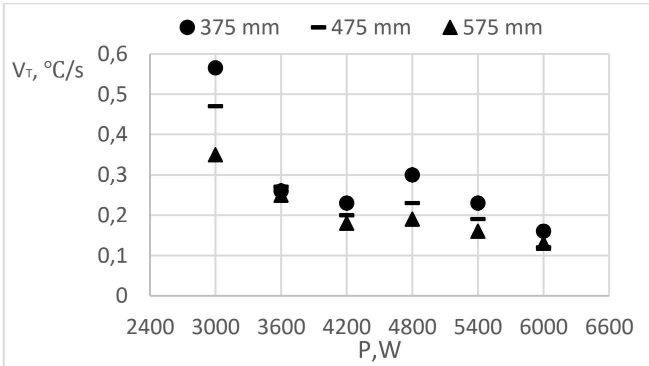

Fig. 5b. Variation of VT with power (P) along flame at 50 L/min air flow rate

Increase in power (P) causes a flame stabilization with an average and reduced value of VT over the flame. Variation of VT with power (P) (Fig. 5.b) and variation of Vy with P (Fig. 6) along the flame indicate at locations y≥ 375 mm similar trend as decrease in the magnitudes of VT and Vy with P as can be given in Table 4. The magnitude of maximum Vy is 0.56 mm/s at P=3000 W at y= 375 mm. It can be estimated that decrease in P is associated with an increase in Vy.

In order to have an overall analysis Table 5 lists the position-averaged magnitudes of VT and Vy for the covered P range and Fig. 7 shows the relationship. Vy variation with VT can be described by the following Eq. 5 in an approximate error band of ± 8 %.

$$Vy = 1{,}1219\,VT - 0{,}0286 \quad (5)$$

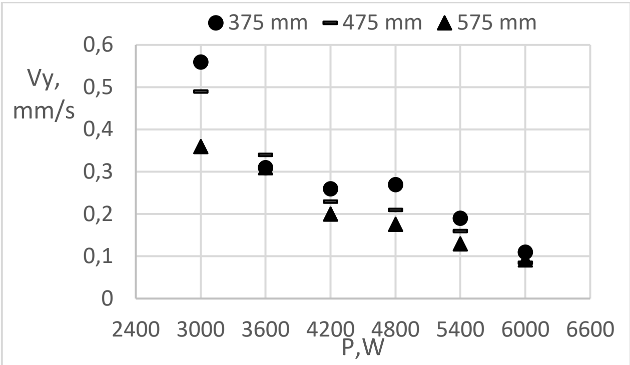

Fig. 6. Variation of Vy with power (P) along flame at 50 L/min air flow rate

Since the magnitudes of TG in the order of 1, VT and Vy are almost identical. Meanwhile as a physical fact thermal speed and growth speed of flame are also close to each other.

Table 4. Calculated magnitudes of VT and Vy

FLOW RATE -POSITION	P (W)	VT °C/ s	Vy, mm/s
50 L/min - 375 mm	3000	0.565	0.56
	3600	0.26	0.31
	4200	0.23	0.26
	4800	0.3	0.27
	5400	0.23	0.19
	6000	0.16	0.113
50 L/min - 475 mm	3000	0.468	0.49
	3600	0.27	0.34
	4200	0.2	0.23
	4800	0.23	0.21
	5400	0.194	0.16
	6000	0.12	0.085
50 L/min - 575 mm	3000	0.35	0.36
	3600	0.25	0.31
	4200	0.18	0.2
	4800	0.19	0.176
	5400	0.16	0.13
	6000	0.13	0.092

Table 5. Position-averaged magnitudes of VT and Vy for 50 L/min

P (W)	**VT (°C/s)**	**Vy (mm/s)**
3000	0,46	0,47
3600	0,26	0,32
4200	0,2	0,23
4800	0,24	0,22
5400	0,19	0,16
6000	0,14	0,1

The comparison with Padala et al's magnitude of flame speed can be done as a concluding remark. Their measured speed is 50 cm/s at 500 W. However, their used time- interval is in the range of 0.1 ms and 1.5 ms. In our case 1 s is our time-interval.

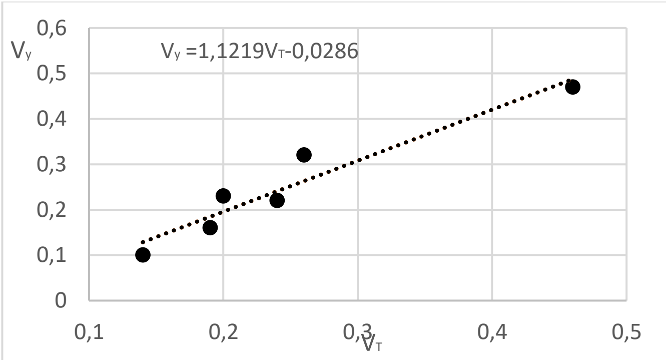

Fig. 7. Variation of Vy with VT (Position averaged at 50 L/min for covered power (P))

Disregarding the differences of range of power and the method of measurement primarily and letting their average timing of 0.8 ms our estimated growth speed Vy can be normalized by a multiplication factor MF = $1/\,0.8 \times 10^{-3}$. Vy =0.56 mm/s can be normalized as Vy = 0.56 x $MF = 700\ mm/s$ which is in the same order of Padala et al's magnitude.

4. Conclusions and Perspectives

Microwave plasma flame generation and flame growth is modeled in this analysis as a function of power (P) for P> 3000 W.

The local temperatures inside the flame are greater with the reduced amount of air rate although increase in input power is causing an increase in the magnitudes of local temperatures. Thermal stabilization of the flame can be described by linear smooth decrease of Ty along flame. Thermal speed (VT) has shown a power stabilization of the flame for high power estimated as P> 4000 W.

In spite of the differences in the studies the overall estimation on flame growth speed Vy is in conformity with the order of magnitude of Padala et al's one.

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