

Vaporisation of Liquid Fuel using Microwaves

Berg K., Siores E., The 8th International Conference on Microwave and High Frequency Heating, University Bayreuth, Germany, 2001.

Abstract

There is no equivalent energy source available to replace the liquid fuel used for combustion. In recent years many replacement energy sources have been developed, however, they are not readily available in comparison to the present liquid fuel. Unless we implement the new technology in order to stretch our resources, the market price for energy will increase exponentially and will have a devastating effect on the world economy. An alternative technique that lowers fuel consumption and pollutants by changing liquid fuel into a gaseous fuel is, therefore, more in demand than ever. This paper presents a different approach in order to utilise microwave energy for vaporising liquid fuel. A preliminary result showed that vaporisation of liquid fuel is possible using microwaves despite its unfavourable dielectric property.

Introduction

There is increasing convergence of opinion that fossil fuels have to be preserved and continued effort has to be made to reduce fuel consumption. With the continued growth of passenger cars and the demand by the industry, it has become more difficult, even with advanced technology, to maintain the trend of further reduction in fuel consumption or even hold the consumption of fossil fuel at a sustainable level world wide. Vaporisation of liquid fuel using conventional heating methods have revealed that a substantial amount of heat energy is required to vaporise a droplet of liquid fuel on a hot plate. These occurrences suggest that heating of liquid fuels for the purpose of vaporisation is inadequate. For this purpose heating using microwave energy was proposed. Specifically, the physical process of liquid fuel vaporisation using microwave energy and under atmospheric pressure was investigated. Effective liquid fuel vaporisation can increase the efficiency of the internal

combustion process and result in a higher engine output and less pollution [1]. This would mean that a gaseous fuel reduces the time of complete combustion. Consequently, a smaller amount of energy is lost in the combustion process that leaves the engine through the exhaust pipe [5].

In this publication the effect of the rate of heating on vaporisation of a given hydrocarbon liquid, such as super unleaded petrol and Diesel fuel was investigated. The investigation was aimed to establish threshold conditions for, (i) the rate of heating or vaporisation as a function of power input and volume vaporised; (ii) the maximum microwave absorption with respect to the material property at elevated temperatures. The properties of liquid fuels have been classified and information about the constituents is available only from independent chemical analysis publications. There are some conditions that should be taken into account with regard to liquid fuels. The liquid fuels should easily evaporate, burn completely at ignition, must be chemically stable, should not form gums or other deposits and has to be free of water.

Methods for vaporising liquid fuels have been improved with the introduction of fuel injectors. In such processes a fine mist of droplets, about a micron in size, is scattered over the rear part of the hot inlet valve to be vaporised. Most of these droplets change into the gaseous state. However, there are usually liquid droplets left unvaporised, suggesting that the combustion is incomplete. The pressure drop by mixing liquid fuel with the high air-velocity passing through the nozzle has improved the vaporisation efficiency [3]. The time required for vaporisation is longer than that required in conventional heating systems. It is hereby hypothesised that a reduction in droplet sizes and heating from inside out can offer an optimum solution. Indeed, this is only possible using microwave energy where heat is applied both ways in relation to their dielectric properties.

An other investigation of hydrodynamic instabilities when heating and evaporating of liquid has been published by Gillon et al [2]. The investigations done by Gillon et al considered (i) volumetric instability within the liquid, also known as Rayleigh-Bernard and (ii) instabilities at the liquid surface known as Marangoni instability domain. It was found that the electromagnetic field transferred the energy through dipolar interaction into the liquid and the heat required for evaporation was transferred by convective circulation to the surface. The electromagnetic field supported the process of evaporation at the surface, as

the temperature became increasingly higher with virtually no heat loss. It even led to hot spots at the evaporating surface. The strong convective circulation, an attribute of the extreme temperature rises, assisted an auto-amplification effect. According to Stuerger and Lallemand [6] the evaporation efficiency was enhanced by the hydrodynamic instabilities known as Marangoni and Hickman instabilities. The acceleration of the evaporation rate was related to thermals, resulting from continuous exchange of cold and hot liquid near the interface. Despite the microwave heating at steady bulk motion of the liquid, the liquid/vapour interface experienced cooling. The temperature rate experienced indicated a competition between the microwave energy and the endothermic behaviour of the vaporisation process. This was shown without convective motions of the liquid. The cooling induced at evaporation was also very effective when the liquid was static. The evaporation rate was found to be proportional to the ratio of the dielectric loss and inversely proportional to the ratio of the vaporisation energy. Generally, this effect can also apply to dielectric materials where the dielectric loss decreases with temperature and therefore conversion of electromagnetic energy into heat is concentrated at cold areas leading to a more unified temperature in the liquid. When the dielectric increases, the hot areas and hot spots cause interfacial instability. The support of thermal internal torpid areas in liquids also indicated its influence at radial thermal profile [4]. An increasing temperature at the centre of a $\varnothing 11$ cm diameter container was investigated, while a $\varnothing 17$ cm diameter container showed a unified temperature profile. It has shown that the microwave energy was confined to the centre of the smaller diameter container. The axial temperature profile increased towards the top and the unsteady liquid surface confirmed the higher microwave energy dissipation. The convective motion of bulk liquid indicated by latex beads was found to be responsible for a uniform temperature distribution. Considering the closed system used by Stuerger and Lallemand the investigation of vaporisation of volatile liquids can be questioned on the grounds that the vaporisation process was restricted by the closed system used. In fact, a true measurement of performance of evaporation can be experimentally achieved by using an infinite volume to expand the vapour. Therefore, the microwave system for investigation of heating and vaporising liquid fuel described in this paper was developed using a simple set up. Consisting of a WR340 rectangular waveguide

applicator at the dominant TE_{10} -mode, where the vaporised liquid can be expand infinitely.

Experimental Set-up

There were two different designs of sample holder to investigate the effects of vaporisation. The liquid fuel was located in the centre position of the applicator. The sample holders design A, see Figure 1, had a constant diameter of $\varnothing 10\text{mm}$ where the liquid level changed with respect to volume. The second design, design B, see Figure 2, had a constant liquid level of 43mm and changed in tube diameter from $\varnothing 2$, $\varnothing 4$ and $\varnothing 6\text{mm}$.

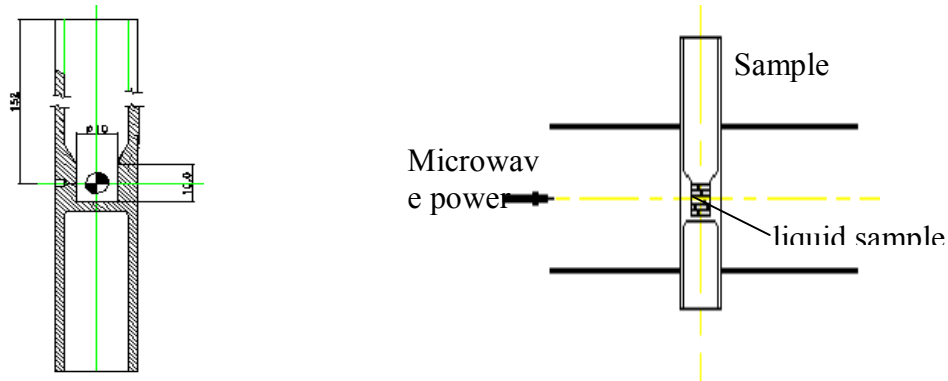


Figure 1: Sample holder design A, the position of the liquid fuel inside the waveguide is also shown.

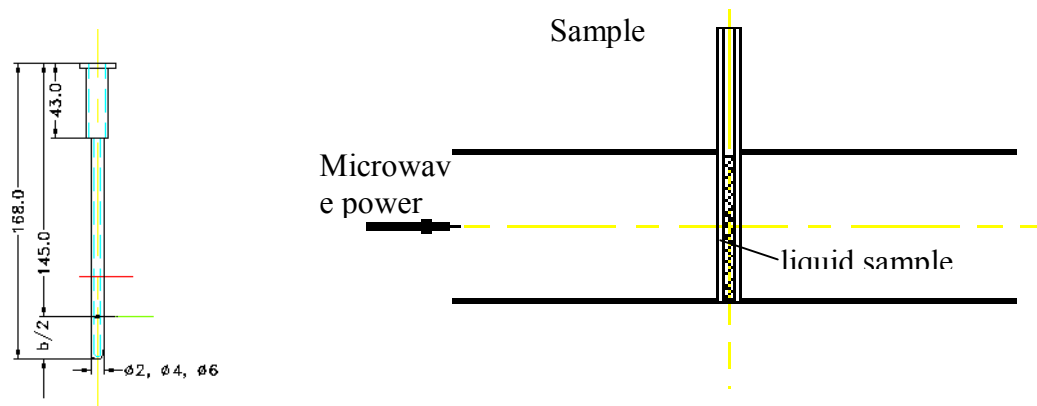


Figure 2: Sample holder design B, also shown is the position of the liquid fuel inside the waveguide is also shown.

The microwave power source used in this study consisted of a water-cooled magnetron, Type NL 10250, model 2KW 54REM at operating frequency of 2.45GHz, 4000Vdc and

was controlled by a microwave control unit, model GMP 20K/SM. The magnetron guide launcher was equipped with a rectangular waveguide flange of specification WR340. The microwave power was adjustable from 0 to 1950W at 2.45GHz. An IR-thermometer was used to measure the bulk surface temperature and it was calibrated against a K-type thermocouple. The WR340 waveguide system was used as part of the resonant cavity with variable tuning achieved in the propagating z-direction using a short circuit arrangement using a non-contacting plunger.

Experimental study: Super unleaded Fuel Investigation

To find out the dielectric properties of liquid fuel, the network analyser HP8510C was used. The analyser was calibrated using known dielectric properties such as distilled water at 20°C and a short circuit at the end of the probe. According to the Debye relaxation theory for permittivity, the dielectric loss experienced a maximum level at the relaxation frequency (f_r). To determine the dielectric property and to define the relaxation frequency (f_r) of the liquid fuel, the measurement of the dielectric was performed using a broadband of frequencies, ranging from 2.2GHz to 20GHz.

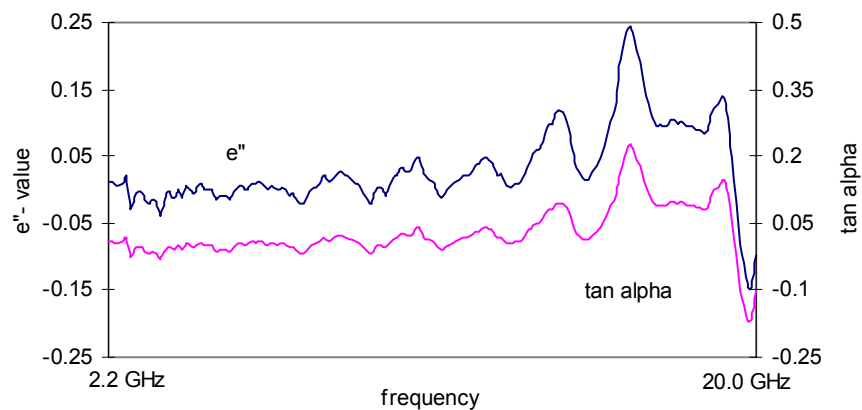


Figure 3: Dielectric property of Super unleaded fuel at 75°C, shown at a the frequency from 2.2GHz to 20.0GHz.

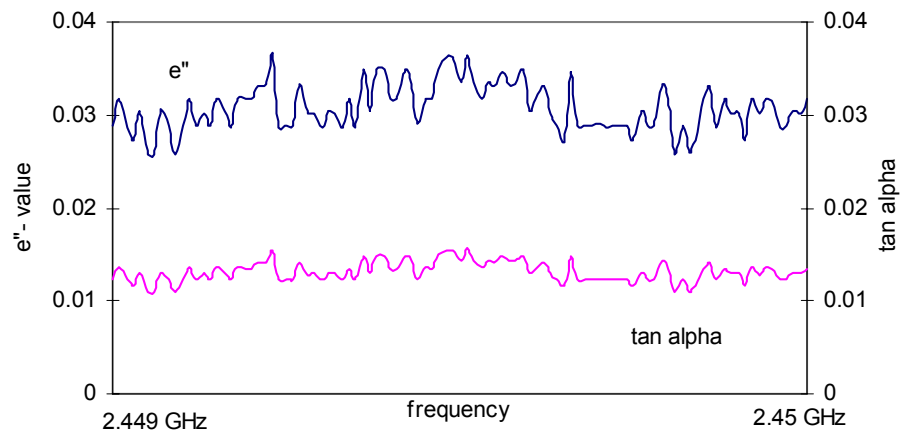


Figure 4: Dielectric property of Super unleaded fuel at 75°C, shown at frequency from 2.449GHz to 2.45GHz.

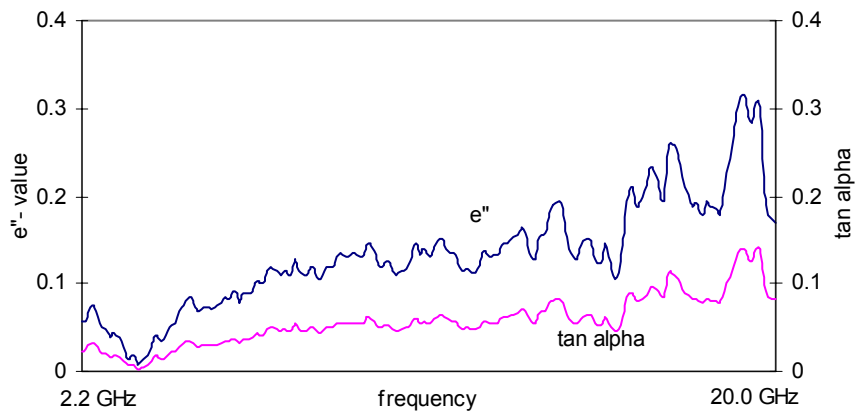


Figure 5: Dielectric property of Diesel fuel at 80°C, shown at frequency from 2.2GHz to 20.0GHz.

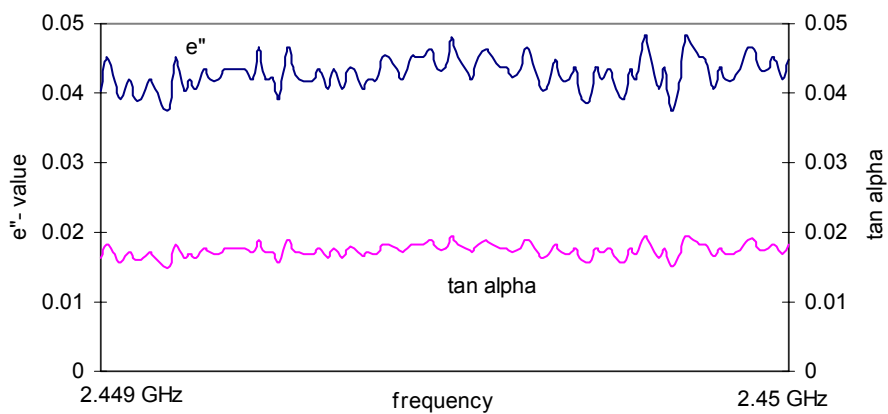


Figure 6: Dielectric property of Diesel fuel at 80°C, shown at frequency from 2.449GHz to 2.45GHz.

The dielectric loss factor (ϵ'') reached its maximum value at the relaxation frequency (f_r) with a high absorption of microwave energy. Consequently, the temperature increase was most efficient and under uncontrolled conditions. The dielectric loss factor (ϵ'') was increasing with the rising temperature and frequency at the broadband measurements, see Table 1. The relaxation frequency (f_r) were observed at higher frequencies and between 16.6GHz to 19.2GHz, see Table 1. The increase of the dielectric loss factor (ϵ'') at 2.45GHz was only minor, see Table 1, suggesting that a strong electromagnetic field would be required to achieve a moderate temperature rate. Limitations in measuring the dielectric property at rising temperatures were caused by the volatility and thermal instability at both fuel liquids and despite the moderate dielectric loss factor (ϵ'').

Table 1: Dielectric loss factor (ϵ'') of Super unleaded and Diesel fuel; f_r = relaxation frequency.

Frequency (GHz)	T e m p e r a t u r e						Fuel
	20°C	25°C	75°C	80°C	90°C	100°C	
2.2	0.0250		0.0006				Super
2.45	0.0308				0.0375		Super
2.2.	0.0710			0.0410			Diesel
2.45		0.0429				0.0451	Diesel
20.0	0.1305		0.0134				Super
20.0	0.3655			0.2301			Diesel
16.6			0.2447				Super (f_r)
16.8	0.4988						Super (f_r)
17.1	0.6580						Diesel(f_r)
17.3				0.2586			Diesel(f_r)
19.2				0.3146			Diesel(f_r)

The difference in vaporisation was related to the test tube holder of design B (Fig.2) that was smaller in diameter and, consequently, the hydrodynamic circulation was unable to be sustained. This proved that hydrodynamic instabilities are important for an efficient vaporisation process. The dielectric property of Super unleaded fuel allowed a moderate temperature rise at 2.45GHz. In this regard, the vaporisation was a continuous process and the defined sample holder restricted the liquid fuel. As mentioned before, this investigation aimed at gaining some information on the application of microwave heating of liquid fuel, where the evaporation of the liquid was a consequence of the heating process. Analysing

the results of Super unleaded fuel, it was found that up to 85% of the maximum temperature was achieved after an average of 40% of the heating time. The performance per unit volume at 1000W and 500W is shown in Figure 6, indicating a maximum temperature of about 145°C at 0.1ml and 1000W. The maximum achievable temperature decreased with an increase in sample volume and changed into a plateau of about 115°C from 0.2ml up to a volume of 0.9ml. This indicates a relationship between the microwave energy and the liquid volume, where the liquid volume becomes rapidly heated at a smaller volume.

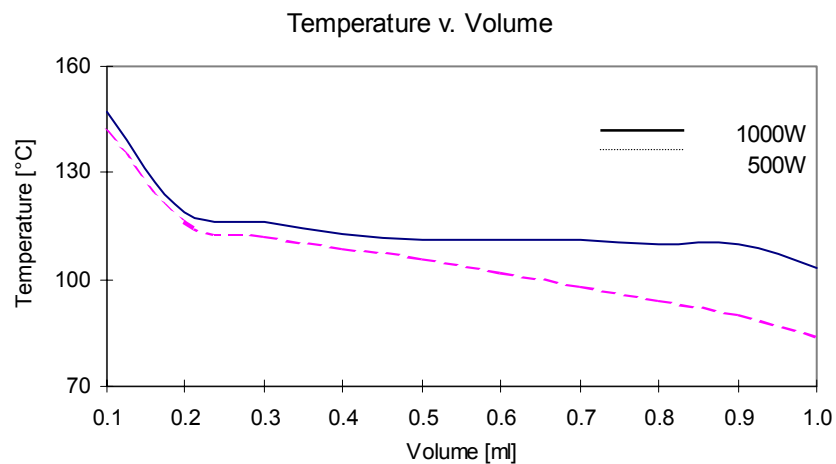


Figure 7: Diagram of volume versus temperature at two different power settings.

An efficient vaporisation process depends on a small droplet size where the best results were achieved at high microwave power. An important factor in the evaporating process is the expansion of the vapour to an infinitive space, preventing a vapour-lock condition. Under a vapour-lock condition the vapour production becomes self-limiting and the process vapour reverses. This was noticed by using design sample holder A (Fig. 1) where the vapour escaped. That was not the case using the design sample holder B (Fig. 2). The effect of the most efficient evaporation is shown in Figure 8. The most effective vaporisation took place at a volume of 0.35ml and a temperature of about 88°C to 92°C for Super unleaded fuel. The vaporisation process was found to depend on temperature, pressure, viscosity, velocity and time.

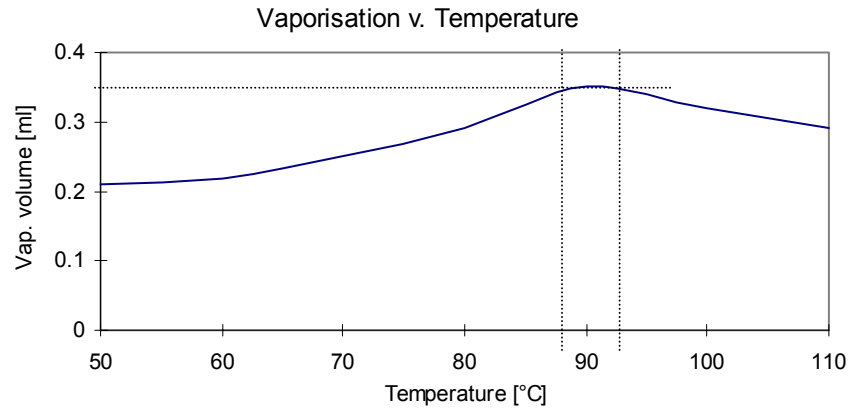


Figure 8: Graphical presentation of the most effective vaporisation.

The curvature, shown in Figure 7, also represents the effectiveness of the vaporisation, achieved using the sample holder of design A (Fig 1). Results can be improved using a larger surface area for vaporisation in conjunction with a reduction in pressure.

Diesel fuel Investigation

The Diesel fuel was investigated using the same technique as used in Super unleaded fuel investigation. The Diesel was heated by the microwave energy more effectively, despite the dielectric loss factor was only 0.08 points higher than Super fuel at 2.45GHz (Table 1). It was noticed that the hydrodynamic activities in the diesel fuel were much stronger than those experienced at Super unleaded fuel. Especially, the instabilities at the evaporating surfaces supported the convective circulation and increased rapidly with the temperature. Just before self-ignition of the Diesel fuel the transparency of the liquid disappeared and ignited with a bright colour. The temperature after ignition has risen rapidly melting the glass-sample holder, however, the process was controlled by reducing the microwave energy. Further tests were conducted below the self-ignition temperature of 250°C. It was observed that even with the strong hydrodynamic activities of the heated liquid the vaporisation of the diesel fuel was much lower than the results gained with Super unleaded fuel.

Conclusion

Vaporisation of Super unleaded fuel through heating using microwaves was achieved. However, the vaporisation of Diesel fuel using microwaves was unsuccessful because of its high vapour point. Super unleaded fuel as compared with Diesel had a lower temperature rate during to microwave heating. Vaporising of Super unleaded fuel was sustainable using microwave heating at both sample holder designs. It was, however, depressed with the sample holder of design B (Fig. 2) because the vaporising supportive convective pattern were missing or could not be established as the tube diameter was insufficient. With a high velocity at the surface, the surface area enlarges physically and supports vaporisation, considering its instability. The liquid temperatures at both designed sample holders A (Fig 1) and B (Fig. 2) were identical. It has been taken into consideration that another physical phenomena known as vapour-lock can affect the vaporisation of liquid fuel, especially, when laboratory tubes are used for testing. The reason behind is the missing turbulence at the liquid surface and the interchange between the air and liquid. If the air circulation belongs to an open system, the risk of creating an explosive mixture would be imminent. When providing a steady withdrawal of vaporised liquid fuel at high surface velocity, the vaporisation will marginally be improved using microwave energy. A combustion engine provides this condition, where a continuous stream of air is required to support internal combustion with fuel. Considering that a microwave driven vaporiser would be integrated in the intake system of a combustion engine it could become an alternative solution for further fuel savings using fuel in gaseous form.

Reference

- [1] J. D. Dale and Oppenheim A.K., "Enhanced Ignition for I.C. Engines with Premixed Gases," *Society of Automotive Engineers, Inc.*, vol. 810146, pp. 606 - 621, 1982.
- [2] Gillon P., Courville P., Steinchen A., and Lallemand M., "Evaporation of Polar Liquids under Low Pressure and/or Microwave irradiation," *Journal Microwave Power Electromagnetic Energy*, pp. 155-166, 1987.
- [3] Marshall E.L. and Owen K., *Motor Gasoline*. Bodmin: Cornwall Hartnalls Ltd, 1995.
- [4] Prosetya H. and Datta A., "Batch Microwave Heating of Liquids: An Experimental Study," *Journal of Microwave Power and Electromagnetic Energy*, vol. 26, pp. 215-226, 1991.

- [5] Seiffert U., *Brennraumuntersuchung mit Lasertechnologie*. Duesseldorf: VDI Verlag GmbH, 1992.
- [6] Stuerger D. and L. M., "An Original Way to Select and Control Hydrodynamic Instabilities: Microwave Heating; Part 2: Hydrodynamic Behaviour of Water and Ethanol under Microwave Heating and Reduced Pressure," *Journal of Microwave Power and Electromagnetic Energy*, vol. 28, pp. 219-233, 1993.