可攜式含添加劑細水霧滅火系統對池火滅火性能評估研究

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摘要

本文基於可攜式含添加劑細水霧滅火系統的噴灑方法對池火的滅火性能及其相對應滅火機制的影響進行一系列的研究。不同的油料種類、噴頭噴灑角度、添加劑溶液的體積濃度、油量及油盆截面積為主要實驗參數。使用油料分別為庚烷、汽油、柴油；噴頭噴灑角度分別為與水平夾角30度、45度、60度；添加劑溶液的體積濃度分別為0%、3%、6%、10%。油量分別為250、500與1000毫升；油盆直徑分別為25與50公分。高噴灑角度時的主要滅火機制為火焰冷卻和氧氣置換；低噴灑角度時為油氣的阻隔與稀釋。本實驗使用的可攜式細水霧滅火系統擁有良好的熱輻射稀釋與降溫能力，對使用者能供良好的保護。細水霧加入添加劑後可使滅火性能極明顯提升，但過多的添加劑反而會造成滅火性能下降。在固定油盆大小的情況下，不同油量的滅火趨勢基本上是相似的。雖然因水霧噴灑造成的不均勻油料表面會稍微減低其燃燒率，這種不均勻的情況在油料厚度到達1公分以上即可改善。固定油料厚度的測試中，油盆直徑50公分的結果異於25公分的，因其較差的水霧覆蓋、較弱的水霧反彈與較多的水霧進入所致。滅火效率不僅受到水霧效應影響, 亦同時受添加劑效應影響。因此對滅火效能而言，必然存在某個細水霧與添加劑間最理想的混合比率。

The Performance Evaluation of Portable Water Mist Fire Extinguishing System with Additive on Pool Fires

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ABSTRACT

A series of tests subjected to various discharge methodologies and fire scenarios are carried out based on a portable water mist fire extinguishing system with additive on pool fires. Different fuel types, nozzle discharge angles, additive solution volumes, amount of fuels and cross-section area of pans are selected as the major experimental parameters. The fuels used are heptane, gasoline, and diesel, the nozzle discharge angles are 30°, 45°, and 60° with respect to the horizon, and the additive solution volumes are 0%, 3%, 6% and 10%. The amounts of fuel used are 250*ml*, 500*ml* and 1000*ml*, and the diameters of pan are 25*cm* and 50*cm*. The dominant mechanisms of restraining fire in the higher nozzle discharge angle regime (>45°) are flame cooling and oxygen-displacement, and in the lower one (<45°) are fuel vapors blocking and dilution. The portable water mist fire extinguishing system used has a good ability for radiation attenuation and temperature reduction that can provide a good protection for the operators. By using water mist with additive, the fire extinguishing efficiencies are

significantly improved. However, if too much additive is provided, the fire extinguishment efficiency will decrease. The tendencies of the fire extinction times for different amount of fuel in a size-fixed pan are similar. Although the situation of non-uniform fuel surface resulted from water mist impingement slightly reduces the burning rate, it can be ameliorated as the height of liquid fuel attains at 1*cm*. In the tests with fixed fuel height, the results of 50*cm* diameter pan different to the ones of 25*cm* diameter since the interactions of its poorer mist coverage, weaker mist jet rebound and more mist reaching. The fire extinguishing efficiency is not only influenced by mist effects but also by additive ones. Therefore, there must be an optimal mixing ration between the mist and additive for fire suppression.

誌謝

承蒙恩師 陳俊勳教授諄諄教誨，除教導研究方法外，更時時匡正做人做事應有態度，讓我碩士生活獲益匪淺。撰寫論文期間，老師更不厭其煩地逐字斧正指導，在此向老師致上萬分感謝。

本篇論文的完成，得格外感謝徐一量教授，因徐博的耐心指導，我才能順利步上研究軌道，更因您的關心照顧，使得工作過程顯得相當愉快。論文口試期間，感謝邱晨瑋教授給予的指正與建議，使得本論文得以更臻完善。

兩年研究所生活中，感謝文奎、大達、文耀、竣翔、文義、振忠、遠達、彥成、靜慈、嘉鴻等學長、姐在生活及課業上的教導。劉維義學長、藍成陽學長、陳寶珠學姐也給了我許多實用建議，使實驗相當溫馨。當然，有了戰友耀文、迪翰、建宏一路上的相互扶持、打氣，讓研究生活更加充實、有趣。感謝交大土地公，在本論文逢瓶頸之際，屢屢助我逢凶化吉。感謝蓉蓉，給我心靈上的依託，讓我保持心情愉快，對未來充滿希望。

最後，由衷感謝我摯愛的爸爸、媽媽，謝謝您們的養育之恩，您們對我的關愛以及充分的信賴、支持，是我努力用功的最大動力。

CONTENTS

LIST OF TABLES

LIST OF FIRGURES

NOMENCLATURE

a	Diameter of pan
A	Cross-section area
A_{pan}	Cross-section area of pan
h	Convection heat transfer coefficient
T	Temperature
T_g	True gas temperature
T_t	Temperature measured by thermocouple probe
T_{w}	Wall temperature of thermocouple
A_w	Cross-section area of thermocouple probe
u_R	Relative uncertainty of each independently measured quantity
S	Coefficient of variation

Greek Symbol

ε	Emissivity of the thermocouple
σ	Stefan Boltzmann constant
α	Absorptivity of the thermocouple

CHAPTER 1

INTRODUCTION

1.1 Motivation

The fixed fire extinguishing systems have already demonstrated their capability in providing the fire protection in a wide range of applications. However, their performances are generally limited by the distribution and allocation of spray nozzles. Portable fire extinguishers, whose spray nozzles are designed as movable and can easily aim at the fire origin, are generally used for the early stage fire control. For portable reasons, the weight of such extinguisher should not be too heavy to carry so its contents should be limited. Thus the portable fire extinguishers usually can only be operated in a short duration, and are inadequate for the larger fire. Also, the water damage is also not acceptable, especially in the situations, where collateral damage by water is undesirable, such as high-tech facilities, aircraft, shipboard engine room, museum, and so on. Therefore, it’s necessary to find a fire control system with longer operating time and less water used not to cause the water damage problem.

The agents, such as carbon dioxide, water foam, dry powder, etc., used in portable fire extinguisher usually have environmental protection and healthy problem. For example, the extinguishers using carbon dioxide as agent are not effective in some cases and always involve the risk of suffocation. In addition, the extinguishers utilizing halogen-based agents are popular because of their non-electric conduction, quick fire-extinguishing and harmless to protection objects. However, halogen atoms are harmful to the atmospheric ozone that has been identified to cause the destructive influence on the natural environment. Therefore, the production of halogen-based agents was banned under the terms of the amended Montreal protocol in 1987. With the inevitable phasing-out of the halogen-based agents, the extensive efforts have been carried out to search for the replacements, such as water mist, compressed-air-foam, and so on. Among which, the water mist used for fire suppression and control is taken as one of the potential alternative agents. The present work is interesting in the application and performance evaluation of portable water mist system by a series of fire tests.

Water mist has been defined as sprays which have 99% of the volume of water droplets less than 1000 microns in diameter [1]. Because of the large surface to volume ratio and long suspension time, water mist shows very effective quenching behavior. Besides, small droplets have the capability of reaching obstructed areas by following the gas flow [2]. In the work of Braidech et al. [3], they found that the corresponding dominant mechanisms for controlling or extinguishing fires are the flame cooling and oxygen displacement. Furthermore, Mawhinney et al. [4] suggested that the mechanisms also include the radiant attenuation, dilution of flammable vapors, and direct impingement wetting and cooling of the combustibles. It is well known that water mist presents the advantages of no toxic, no corrosion, and no environmental problems. Besides, the amount of water used in water mist system is much less than that used in the conventional one, so the collateral water damage is much smaller.

The operation units of water mist system are shown in Fig.1.1, which are similar to the ones used in sprinkler system. Since water mist system is operated in a higher pressure condition than that of sprinkler system, the corresponding pipes, pumps, and valves should have the capabilities to sustain the high pressure, sometimes to 150bar (2175.54psi) for high pressure system. According to Fig.1.1, the fixed water mist system could be transformed into portable or moveable one, if we redesign the water supply system, power source and pump.

For the operating pressure, the water mist system can be divided into three categories: the high-, medium- and low- pressure water mist systems. When the operation pressure is greater than 34.5bar (500psi), it's called high pressure system. When the operation pressure is lower than 12.1bar (175psi), it is called low pressure system. The one in between is medium pressure system. In the present study, the portable water mist system belongs to high pressure one.

For more efficient fire-extinguishing performance, many kinds of additives for water mist have been developed. However, there are limited researches on the application of additive in a portable system. Applying the additives to portable water mist system, less water and fire extinguishing time are expected to take in fire suppression. It could make portable water mist system more efficient and practical in various scenarios of fire. But some additives have serious shortcomings in application, such as corrosion to equipment by the inorganic metal additives and toxicity to human beings by the organic additives, and they could not improve the fire-extinguishing efficiency of water mist greatly either [5].

The burning rates of diffusion flame while is the combustion from pool fires, are related with the vaporizing rates of the fuel, further related with the cross-section area of pan. However, the larger the cross-section area of pan is, there is more mist being able to reach the fuel surface. It is worth to investigate these effects on the performance of fire extinguishment. Furthermore, in the same cross-section area of pan, the amount of fuel used affects its thickness. It is interesting to know whether the thickness of the fuel would influence the performance of fire extinguishment as well. Thus, diameter of pan and amount of fuel are considered as the different fire scenarios.

1.2 Literature Review

According to NFPA 750 [1], water mist is defined as sprays that 99% of the volume of the spray droplets under the flow-weighted cumulative distribution are with the diameters less than 1000 microns at the minimum design operating pressure of water mist nozzle. The cumulative volumetric distribution of water droplets is to be reported as the flow rate per unit area weighted distribution of water droplets, measured at the radial array of the 24 measurement locations, which are symmetrical with respect to the central axis of the water mist nozzle at 1.0 *m* below the tip of the nozzle. The configuration is shown in Fig. 1.2. The nozzle droplet size distribution to be reported is a single summation of the weighted cumulative count and volume percent droplet distributions for all measurement locations.

Grant et al. [6] reported the spectrum of droplet sizes, as shown in Fig. 1.3, where the most interesting 'average' size range for fire fighting is deemed to be from 100 to 1000 μm. Afterward, a mist classification system based on a 'cumulative percent volume' distribution plot was proposed by Mawhinney and Solomon [7], which make distinguishment between 'coarser' and 'finer' water sprays, as shown in Fig. 1.4. The more drops of 'fine' sizes contain in sprays, the more rapidly sprays evaporate in the fire environment and facilitate the characteristic extinguishment mechanisms of water mist. However, in practice, sprays for which the D_{v90} (90% volume diameter) is less than or equal to 400 μm, are suitable to the suppression of liquid pool fires or where 'splashing' of the fuel is to be avoided. Sprays for which have the D_{v90} of 400-1000 μm are the better choice for the case of fuel wetting being tolerable, for example, when tackling Class A fires.

The fire extinguishion performance of water mist system depends on its characteristics (e.g., droplet size, spray angle, spray pattern, water flow rate, and momentum) and discharge methodologies (e.g., the nozzle discharge angle and timing and the configuration in the compartment). A large number of studies on pool fire scenarios by using water mist as fire extinguisher have been carried out. Mawhinney [8] used a twin-fluid nozzle to produce a fine spray to extinguish liquid pool fire. It was found that spraying down directly onto the flame is the most effective means of extinction. Any obstructions placed in the path of the spray lower both the spray’s momentum and the amount of water suspended in the air as mist, and result in a reduction of its capacity to extinguish the fire.

Kim et al. [9] investigated the fire extinction limit and the enhancement for a gasoline pool fire interacting with water mist system. The fire extinction limit was obtained from the minimum nozzle injection pressure measured as the fire extinguishment took place. It was shown that there are two distinct regions, a fire extinction region and a fire enhanced one, in the relationship between the injection pressure and the distance from the nozzle to the fuel pan. In the fire enhanced region, the larger the spray thrust, the lager the burning rate is. It was also revealed that the effective water flux appears to be a more useful parameter than the injection pressure for the fire extinction limit.

Yao et al. [10] investigated the interaction of water mists with a diffusion flame in a confined space with proper ventilation control. It was shown that the poorer is the ventilation, the easier the suppression. Water mists can suppress the diffusion flame of pool fire in the confined space through oxygen displacement, evaporative cooling and heat radiant attenuation. On the other hand, it can also enhance the combustion through the mixture expansion and chain reaction. When the water mists with enough volume flux are applied to the diffusion flame in confined space, suppression effect can play a more dominating role than enhance one. Besides, the water mists can affect the smoke release rate and its movement, and have a more complex effect on the solid sample than on the liquid one.

Richard et al. [11] conducted an experimental study for the effect of water mist addition on a small-scale heptane pool fire. The obtained mapping of the temperature and extinction coefficient due to soot and water droplets has provided new information about the flame structure. It showed that the extinction with water mist is rather obtained by a rapid and total clearance of the liquid, than from the reduction of the burning rate. Water mist has the primary purpose to cool the flame and to push water vapors onto the fuel surface, but it can also increase the level of temperature significantly and its own fluctuation in this zone. Furthermore, Richard et al. [12] conducted a phenomenological study on the effect of water vapor addition through the base of a small-scale heptane pool fire. Heptane, suspended on a pool of liquid water, burned as a pool flame while the water underneath was heated to boiling. Water vapors were added into the diffusion flame, where chemical reactions and air entrainment took place. It was shown that the addition of water vapors in such a way affects both physical phenomena (inhibiting the soot formation) and chemical reactions (shifting CO to CO_2). The effects of water vapor addition were further confirmed by injection of an inert gas instead of water vapor. The fire temperature was significantly decreased since the resulted heat release was not sufficient enough to counteract the cooling effect of water vapor.

Kim and Ryou [13] investigated the fire suppression characteristics of water mist system for the pool fire. The fire extinction time, the oxygen concentrations, and the temperature fields in the enclosed compartment were measured. It was shown that the temporal variations of the smoke layer temperature can be divided into two different regimes: the initial sudden cooling regime and the gradual cooling one, by a critical cooling time, defined as the time during which the sudden cooling persists.

Previous researches have shown that it is very difficult for water mist to extinguish flammable liquid fires with flash points below normal ambient temperature, such as n-heptane (C_7H_{16}, FP = -4°C), because the fuel temperature cannot be cooled down enough to reduce the vapor/air mixture above the fuel surface below its lean flammability limit [14].

Not too many researches concerned on the capability and limitation of portable water mist fire extinguishers were found. Liu et al. [14, 15 and 16] carried out a series of full-scale fire tests by using portable water mist extinguishers to suppress various types of fires, including cooking oils, n-heptanes, diesel fuels, wood cribs and energized targets. For the heptane fire, experimental results showed that its extinguishment process can be divided into three phases. In phase I, the heat release rate is increased as the fresh air is brought into the flame by water mist discharge. In phase II, a large fireball suspended in the air expands rapidly with continuous water mist discharge. In the last phase, the fire is extinguished as water mists cover the entire fuel surface. The heptane fire, which has a high surface temperature, is extinguished mainly through both flame and fuel surface cooling. For the diesel fire, comparing to the heptane one with the same size of fuel pan, it is much easier to extinguish, because the diesel fuel has a higher flash point (FP = 60°C) and a lower heat release rate. Besides, the surface temperature of diesel fuel is higher than that of heptane fuel and the burning rate of diesel is affected by the fuel cooling owing to the presence of water mist. The diesel flame is also enlarged under the attack of water mist, but its maximum size is much smaller than the one caused by heptane fuel, because it generates less volatile fuel vapor.

In order to further improve the fire-extinguishment performance of water mist, many kinds of additives have been developed in the past years. Zhou et al. [17] conducted a phenomenological study for the effect of MC (multi-composition) additive on water mist's fire-extinguishing efficiency through the base of the ethanol, diesel and wood crib fires. They combined the physical and chemical mechanisms of fire suppression to explain the reason why the MC additive could improve the fire extinguishing efficiency. With MC additive presented, the oxygen is isolated and the radiative feedback from the fire to the fuel is mitigated by fluorocarbon surfactant, which forms a thin film layer over the pool or wood surfaces. The reaction and the flame spread are inhibited by the organic metal compound, which produces active radicals in the course of fire extinguishment. Energy of fire is absorbed by the decomposable material, which decomposes under high temperature condition and produces a lot of inert gases. It was found that adding a small quantity of MC additive into the water mist significantly improves the performance of the water mist system in suppressing fires. However, if too much MC additive is applied, the fire extinguishment efficiency will decrease.

Besides the studies of the pool-type fire, the other extensive researches in applications of water mist system have been done. In order to have a more complete understanding of the characteristics of water mist and the mechanisms of extinguishment, the following literatures are introduced. Liu et al. [18] investigated the extinguishment performance of the water mist system using two water mist discharge modes, continuous and cycling, in a series of full-scale fire tests of a twin-fluid water mist system in an empty enclosure and in a simulated machinery space, respectively. They found that water mist system using the cycling discharge has a better performance for fire suppression than that using the continuous one. It is because the recurrent dynamic mixing generated by the cycling water mist discharge can make higher depletion and dilution rate of oxygen in the compartment.

Weng and Fan [19] investigated the mitigation of backdraft with water mist system in a reduced-scale test series. It showed that water mist is an effective mitigating tactic able to suppress backdraft in a building fire. The way water mist to mitigate backdraft is primarily by means of reducing the unburned fuel mass fraction, rather than by a thermal mechanism of cooling.

Qin et al. [20] investigated the suppression of cooking oil fires with water mist system in small-scale experiments using cone calorimeter. Cooking oil fires are difficult to extinguish since they are easy to re-ignite. Such fires are classified as Class F by National Fire Protection Association. It was shown that good design of the system can suppress peanut oil fire effectively. On the contrary, improper design may result in the adverse effects by enhancing the combustion, producing more carbon monoxide and giving out more dark smoke. Liu et al. [21] indicated that cooking oil fires are very difficult to extinguish, because they burn at high temperature and re-ignite easily due to the change in oil composition during heating and fire suppression. Cooking oil fires can be effectively extinguished and prevented from re-ignition by water mist systems. The spray angle, discharge pressure and water flow rate are important factors to determine the effectiveness of water mist in extinguishing cooking oil fires.

Shu et al. [22] evaluated the performance of a water mist system in the fume exhaust pipes used in semiconductor facilities by comparing with that of a standard sprinkler system. The parameters considered were the amount of water that the mist nozzles used, air flow velocity, fire intensity and operating pressure. It was found that the droplet size in a water-related fire protection system plays a critical role. Water mist system can produce a better performance than that of a standard sprinkler one, and furthermore a higher operating pressure of water mist system can achieve a better performance.

Ye et al. [23] investigated the suppression of passive and active explosions with water mist system in a field-scale pipe. The experimental results showed that the larger the mist density and the length of water mist suspended inside the pipe are, the better the suppression effect becomes, and both passive and active explosion suppressors can fully quench the explosion of methane-air mixture with the filling of enough water. Tam et al. [24] explored the potential application of the Micromist device as a soft suppressive barrier. The Micromist device was based on a proprietary hot-water technology, which allows the production and distribution of a very fine mist suitable for damping down the propagating flame. It was shown that the Micromist device is able to arrest a developing gas explosion even though the water droplet loading is not sufficient to arrest the flame and the severity of the gas explosions can be much reduced.

1.3 Scope of Present Study

The structure of schematic diagram of the thesis is shown in Fig. 1.5. In this study, the effects of high pressure water mist system discharge methodologies on the performance and the corresponding mechanisms of restraining fire are studied. The fire source is a pool-fire burner and the fine water spray is injected from a portable device in an open environment, and the additive added in water mist is neither toxic nor corrosive. Different nozzle discharge angles, fuel types, additive solution volumes, amount of fuels and cross-section area of pans are selected as the major experimental parameters. The objective of this study is to investigate the effects between directions of water mist injected and the resultant fire-extinguishment performance. Furthermore, a phenomenological study is conducted on the effect of additive to water mist with different fuels.

CHAPTER 2

EXPERIMENTAL APPARATUS

All of the experimental apparatus are set up in a test field, whose dimensions are 25-meter long, 9-meter wide and 7-meter high. In this test environment, all the tests were regarded as fuel-controlled because the air supply is unlimited. The test facility consists of a pan, in which is filled with assigned fuel, the portable water mist system and the measurement instruments. The above-mentioned elements are described in details as follows.

2.1 Experiment Layout

The schematic configuration of the experimental apparatuses is shown in Fig. 2.1. The fuel pan was placed in the center of the test field and the mist nozzle was fixed on a frame. The mist discharge nozzle angle could be adjusted from 0 to 90 degree measured from the horizon for different test scenarios. The mist nozzle was connected to high-pressure pump through a soft hose. The release pressure could be adjusted by the pressure valve in the pump and was indicated on the pressure gauge attached behind the nozzle. The fire temperatures were measured by a thermocouple tree set up in the center of the pan. A radiometer was employed to observe the radiant attenuation effect of mist. All measured data were transferred to the disk storage using a PC-controlled data acquisition system.

2.2 Parameters of Tests

The parameters of fire tests included fuel type, nozzle discharge angle, additive solution volume, amount of fuel, and cross-section area of pan. The fuels used were heptane, gasoline, and diesel. Nozzle discharge angles were 30°, 45°, and 60° with respect to the horizon, and the additive solution volumes were 0% (pure water), 3%, 6% and 10%. The amounts of fuel used were 250*ml*, 500*ml* and 1000*ml* respectively, and the diameters of pan are 25*cm* and 50*cm*. For each pool fire, the tests used three different nozzle discharge angles and four different additive solution volumes. Each fire test was carried out at lease three times for data consistence.

2.3 Fuels and Fire Extinguishment Agents

2.3.1 Fire Source

The small-scale pool fires were generated by using heptane, gasoline or diesel as the fuel, which were contained in a circular stainless pan with a diameter of 25*cm* and a height of 15*cm*, as shown in Fig. 2.2(a). In the middle-scale one, the pool fire was generated by using heptane, which was contained in a circular stainless pan with a diameter of 50*cm* and a height of 15*cm*, as shown in Fig. 2.2(b). The pans were mounted on a steel stand 15*cm* above the ground to minimize the effects of surrounding ground surfaces on the behaviors of the fire.

The properties of these fuels are shown in Table 2.1. Heptane was chosen as one of the test fuels because it has the advantage of a fixed boiling point (98°C) below that of water. As a consequence, it does not experience any serious splashing effect caused by water droplets. Besides, its low flash point temperature (-4°C) and high vapor pressure could extend the experimental time since it was not easy to reduce the vapor/air mixture ratio below its lean flammability limit. On the other hand, gasoline and diesel were chosen as the contrast reason because of their different characteristics in fire suppression as comparing to that of heptane.

For the tests of heptane and gasoline, the pan was filled with 750*ml* of water and 250*ml* of fuel, that is, total height is 2*cm*. The fuel was above the water and they were not mixed. The fuel was allowed to pre-burn for 60*s* to ensure to reach the quasi-steady burning before the mist system activated. For the test of diesel, an extra of 50*ml* gasoline, served as the accelerator, was given, because diesel is hard to ignite due to its high flash point temperature (>52°C). Then, the fuel was allowed to pre-burn for 120*s* to ensure the burnout of gasoline and the quasi-steady burning was reached before the mist system released.

2.3.2 Water Mist System

The high pressure water mist system was made up of two major components, the high pressure pump and nozzle. The high pressure pump, shown in Fig. 2.3, could produce 130-*bar* of pressure and the corresponding flow rate be up to 13 liters per minute. However, it was not easy to observe the fire extinguishment process under such a high pressure because the complete extinguishment occurs immediately after the discharge of water mist. Therefore, a critical pressure 35 *bars*, a minimum water mist injection pressure required for fire extinction for a distance of 1*m*, was chosen for the purpose of having enough experimental duration. The high pressure water mist nozzle used was a commercial one, as shown in Fig. 2.4. It relies on hydraulic pressure to force water flowing through the small diameter orifices with a high velocity and to form the water mist. The spray angle of the nozzle is 60°, and the mean droplet size of the water mist is 200 microns in diameter. The K factor of the nozzle was 1.16 $l/min/bar^{1/2}$, indicating that the flow rate was 11.6 liter per minute at a pressure of 100 *bars*. Because orifices' diameter was so small that it was possible to be obstructed. Once the path of mist was obstructed, it would affect the effective water fluxes very much. Therefore, the water used in experiments was pre-filtered to remove its impurities beforehand.

2.3.3 Water Mist Additive Property

The water mist additive used was made of 97% fire-retardant chemical, 1.8% surfactant, 0.6% mint and 0.6% camphor and it was proofed non-toxic. The components of the fire-retardant chemical includes critic acid (molecular formula: $HOC(COOH)(CH_2COOH)_2$), borax ($Na_2B_4O_7 \cdot 10H_2O$) and salt (molecular formula, NaCl). The additive is able to form a thin layer of foamy film on the fuel surface after being sprayed out from the nozzle. Such foamy film can isolate the oxygen, block the fuel vapors, and mitigate the radiative feedback from the fire to the burning fuel surface, so that it makes the fuel hard to re-burn.

2.4 Measurement Instrumentations

2.4.1 Temperature Measurement

A thermocouple tree, shown in Fig. 2.5, was set up in the center of the pan to measure the temperatures. Four K-type thermocouples were installed on that. They were marked as #1, #2, #3 and #4, respectively, and their corresponding locations was given in Fig. 2.6. Thermocouple #1 was located at 0.5*cm* below the fuel surface and 12.5*cm* from the side wall of the pan to measure the fuel temperature. Thermocouple #2 was at the interface of fuel and air to measure the fuel and the subsequent flame temperatures. The last two thermocouples (#3 and #4) were located 15*cm* and 30*cm*, respectively, above the fuel surface to measure flame and its plume temperatures.

2.4.2 Radiation Heat Flux Measurement

The radiometer (Type 64 SERIES, MEDTHERM) is shown in Fig. 2.7. It was installed beneath the nozzle, about 70.7*cm* from the pan, as shown in Fig. 2.1, to collect the radiation heat flux from flame. The radiation heat flux is absorbed at the sensor surface and is transferred to an integral heat sink that remains at a different temperature from the one of sensor surface. The temperature difference between two selected points along the path of the heat flow from the sensor to the sink is the functions of the heat being transferred and the net absorbed heat flux. The transducer has thermocouples or thermopiles to form a differential thermoelectric circuit, thus providing a self-generated emf at the output leads that is directly proportional to the heat transfer rate. No power supply or thermoelectric reference junction is needed. The certificate of calibration is shown in Fig. 2.8. The full scale output level of the radiometer is $10.23\,mV$ at $10\,\mathrm{B}tu/(ft^2 \cdot s)$, and its responsivity is $1.023\,mV$ per $\mathrm{B}tu/(ft^2 \cdot s)$. Besides, a water-cooling system, shown in Fig. 2.9, is used in order to protect the transducer from being overheated. Cooling water, about 30°C in the flow rate of 10.7 *ml/s*, is provided from one of the water tube attached to an underwater pump, and then warm water is released from the other water tube. Water cooling system should be provided since un-cooled transducer might rach above 400F (204.44°C).

2.4.3 Hydraulic Pressure Measurement

A pressure gauge, shown in Fig. 2.10, was installed in the pipe near the nozzle to monitor the discharge pressure of the water mist system. The applied hydraulic pressure of 35 *bars* was chosen in such a way that complete extinguishment did not occur immediately or even did not occur at all in order to earn enough time for experimental purposes. The volume flow rates of mist in different additive solution volumes are listed in Table 2.2. It shows that the volume flow rates are almost the same in the in different additive solution volumes so that the added additive does not significantly affect the run-off of water mist.

2.4.4 Oxygen Concentration Measurement

Part of burnt gas products are collected from the fire, and sucked into the Gaseous Oxygen Analyzer (Model 755A, Rosemount Analytical), shown in Fig 2.11 to measure the oxygen concentration within the fire. Before measuring and analyzing the gas samples in the instrument, a preconditioning process is carried out in advance. The preconditioning system includes two tandem connection sets of glass wool filters, a set of membrane filter, a gas cooler and a micro pump, which are indicated in Fig 2.12.

2.4.5 Data Acquisition

All experimental data were recorded by a data acquisition system (Type 5000, Jiehan) with 2*s* sampling interval. The picture of the datalog is shown in Fig. 2.13.

2.4.6 Digital Video

One digital video camera (Type DCR-TRV40, SONY), fixed at an appropriate position, was used to provide visual records of the fire, water mist discharge, and fire suppression process. The images from the video were transmitted to a PC by IEEE 1394 card, and they were processed by the CyberLink PowerDirector software to show a series of flame structures.

2.5 Procedure of the Experimental Operation

(1) Set the nozzle discharge angle at 30° from the ground (horizon). Prepare sufficient water without additive (pure water) for fire suppression.

(2) Turn on and calibrate the instruments, such as the radiometer and

datalog, to make sure their stabilization and performance accuracy before performing the experiment.

(3) Check if any impurity blocks off the orifices of the nozzle.

(4) Turn on the water cooling system of the radiometer to prevent it from overheating in the whole experimental process.

(5) Pour 750*ml* water into the pan.

(6) Pour 250*ml* heptane fuel into the pan. Then, wait a moment until the fuel floats on water surface uniformly and stably.

(7) Pre-record the temperature and radiation heat flux, and activate the digital video before the pool fire is ignited.

(8) Ignite the fuel and wait for 60*s* pre-burn time to reach quasi-steady burning before the water mist system is released.

(9) Turn on the high pressure pump, which can produce a hydraulic pressure to force water through the nozzle to discharge the water mist. Turn it off as the fire is extinguished.

(10)Turn off the measurement apparatuses as the test is ended. Re-ignite the pan to examine if the fuel is burned out. Then, start the exhaust systems to exhaust the combustion products out of the test field until the test environment returns to the normal state and is ready for next test.

(11)Change the fuel to gasoline and diesel in order, as a parameter. Repeat the procedure from (5)-(10) steps. Note that if diesel is used in step (6), it should add an extra of 50ml gasoline to assist in igniting and the pre-burn time in step (8) should change to 120*s*.

(12)Change the nozzle discharge angle to 45° and 60° in order, as a parameter. Repeat the procedure from (1)-(11) steps.

(13)Change the additive solution volumes to 3%, 6%, and 10% in order, as a parameter. Repeat the procedure from (1)-(12) steps.

CHAPTER 3

UNCERTAINTY ANALYSIS

All of the data from experimental results may not be equally good to adopt. Their accuracy should be confirmed before the analyses of experimental results are carried out. Uncertainty analysis (or error analysis) is a procedure used to quantify data validity and accuracy [25]. Errors always are presented in experimental measuring. Experimental errors can be categorized into the fixed (systematic) error and random (non-repeatability) error, respectively [25]. Fixed error is the same for each reading and can be removed by proper calibration and correction. Random error is different for every reading and hence cannot be removed. The objective of uncertainty analysis is to estimate the probable random error in experimental results.

From the viewpoint of reliable estimation, it can be categorized into single-sample and multi-sample experiments. If experiments could be repeated enough times by enough observers and diverse instruments, then the reliability of the results could be assured by the use of statistics [26]. Like such, repetitive experiments would be called multi-sample ones. Experiments of the type, in which uncertainties are not found by repetition because of time and costs, would be called single-sample experiments.

3.1 Analyses of the Propagation of Uncertainty in Calculations

Uncertainty analysis is carried out here to estimate the uncertainty levels in the experiment. Formulas for evaluating the uncertainty levels in the experiment can be found in many papers [26, 27] and textbooks [25, 28, 29]. They are presented as follows:

Suppose that there are n independent variables, $x_1, x_2, \ldots, x_n$, of experimental measurements, and the relative uncertainty of each independently measured quantity is estimated as u_i. The measurements are used to calculate some experimental result, R, which is a function of independent variables, $x_1, x_2, \ldots, x_n$; $R = R(x_1,\ x_2\ ,\ldots,\ x_n)$.

An individual x_i, which affects error of R, can be estimated by the deviation of a function. A variation, δx_i, in x_i would cause R to vary according to

$$\delta R_i = \frac{\partial R}{\partial x_i}\delta x_i \tag{3.1}$$

Normalize above equation by dividing R to obtain

$$\frac{\delta R_i}{R} = \frac{1}{R}\frac{\partial R}{\partial x_i}\delta x_i = \frac{x_i}{R}\frac{\partial R}{\partial x_i}\frac{\delta x_i}{x_i} \tag{3.2}$$

Eq. (3.2) can be used to estimate the uncertainty interval in the result due to the variation in x_i. Substitute the uncertainty interval for x_i,

$$u_{R_i} = \frac{x_i}{R}\frac{\partial R}{\partial x_i}u_{x_i} \tag{3.3}$$

To estimate the uncertainty in R due to the combined effects of uncertainty intervals in all the x_i's, it can be shown that the best representation for the uncertainty interval of the result is [27]

$$u_R = \pm\left[\left(\frac{x_1}{R}\frac{\partial R}{\partial x_1}u_1\right)^2 + \left(\frac{x_2}{R}\frac{\partial R}{\partial x_2}u_2\right)^2 + \ldots + \left(\frac{x_n}{R}\frac{\partial R}{\partial x_n}u_n\right)^2\right]^{\frac{1}{2}} \tag{3.4}$$

3.2 Uncertainty Level Analysis in the Experiment

The surface area of pool is selected to demonstrate the process of uncertainty level analyses as follows.

The surface area of pool, A_{Pool}, is

$$A = \frac{\pi}{4} \times \mathrm{a}^2, \quad a = 250 \pm 0.5mm$$

$$A = A(a)$$

$$u_A = \pm\left[\left(\frac{a}{A}\frac{\partial A}{\partial a}u_a\right)^2\right]^{\frac{1}{2}} = \pm\left[(u_a)^2\right]^{\frac{1}{2}} = \pm 0.002$$

$$(u_a = \frac{0.5}{250} = 0.002)$$

3.3 The Asymmetric Uncertainties of Thermocouple

Room temperatures are measured by a 1mm diameter K-typed thermocouple, whose signals are sent to a PC-record (Ethernet). The accuracy of the thermocouple itself without coating is ±0.2%. Due to the effects of conduction, convection, and radiation, it is worthwhile to check the correctness of gas temperature measured by such K-typed thermocouple. Via an application of energy balance, i.e.,

Energy in = Energy out, or

Convection to the junction of thermocouple = Radiation from the junction of thermocouple + Conduction loss from the probe

Because of the fine thermocouple (1mm), the conduction term can be neglected. Then, the steady-state energy equation can be rewritten as follows.

$$A_w h(T_g - T_t) - A_w \sigma(\varepsilon T_t^4 - \alpha T_w^4) = 0 \tag{3.5}$$

In practice, the flame temperature is much higher than the wall temperature of thermocouple, so the absorption term, αT_w^4, from the relatively low wall temperature of thermocouple can be removed from Eq. (3.5). According to Eq. (3.5), the expression of correlation is given as:

$$T_g = T_t + \frac{\varepsilon \sigma T_t^4}{h} \tag{3.6}$$

where T_g = the true gas temperature

T_t = the temperature measured by thermocouple probe

ε = emissivity of the thermocouple

σ = Stefan Boltzmann constant

h = convection heat transfer coefficient at wire surface

Now, the analysis method of uncertainty can be utilized to obtain the uncertainty in the flame temperature from the correlation associated with h, T_t, and ε. The relationship between temperature and error is shown in Fig. 3.1.

3.4 The Uncertainties of Radiometer

The radiometer (Type 64 SERIES, MEDTHERM) is provided with the certified **c**alibrations, compiled with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A. Calibrations, shown in Fig. 2.8, are corrected by the National Institute of Standards and Technology through temperature standards and electrical standards. The uncertainty of its performance is 3%, shown in the report as well.

3.5 The Experimental Repeatability

In order to confirm the accuracy and coincidence of experimental data, each fire test under the specified fuel, discharge angle and additive volume rate was carried at least three times to ensure the repeatability. The following examples are use to illustrate the creditability in the previous statement. There are two cases selected to demonstrate the experimental repeatability. Firstly, pure water tests with different fuel types in 25cm diameter of the pan is selected. Secondly, water mist with additive in 50*cm*-diameter of pan with heptane fires is selected as well. It recorded three measured data of extinction time and made an average value for each fire test. The three measured data, their averaged value, and the coefficient of variation are listed in Table 3.1. The coefficient of variation (C.V.) is defined as the ratio of the standard deviation s to the mean $\overline{X}$, where the standard deviation s is calculated as:

$$s = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2} \tag{3.7}$$

The coefficient of variation is a dimensionless number that allows comparison of the variation of data points in a data series around the mean. Figure 3.2 graphically shows the presentation of Table 3.1. The averaged values formed a dashed curve. It can be seen that in general the coefficients of variation are within the acceptable range since the maximum is below 10%, consequently, the experimental repeatability is quite good. The fire extinguishment processes and their corresponding characteristics will be discussed in details in next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

In general, water-related fire protections or sprinkler system are not suggested to use for Class B fires since most of liquid will splash over the water. Therefore, it is difficult to cool down the fuel surface with water evaporation and possible to encounter with a ‘running liquid fire’. However, for water mist system the momentum is insufficient to cause the liquid fuel to float over, since its water amount is only 1/10 of that used in the traditional sprinkler system. Besides, with a much lager surface to volume ratio, water mist can greatly enhance both evaporation rate and suspension time for cooling down the liquid fuel surface. It has been proved that water mist system can suppress Class B fires effectively with proper design and operation. In this study, a series of fire tests using water mist as the extinguisher were conducted in a test field. Several fire scenarios and discharging features were designed to evaluate the fire suppression performance of a portable water mist system with additive in order to identify the controlling mechanisms of fire suppression. Table 4.1 shows the list of variables, which include fuel type, additive solution volume, nozzle discharge angle, amount of fuel and cross-section area of pan. The range for each variable are also listed in this table.

4.1 Fire Tests with Different Fuel Types

The tests were performed with diesel, heptane and gasoline fires respectively. The fuels were contained in a circular stainless pan, with a diameter of 25*cm* and a height of 15*cm*. For the tests of heptane and gasoline fires, 750*ml* of water and 250*ml* of fuel were used. For the tests of diesel one, an extra of 50*ml* gasoline, served as the accelerator, was given.

4.1.1 Pure Water Mist

In this section, pure water mist was used as the fire suppression agent and the corresponding results would be taken as the base data for comparisons with those using additive. The extinction times for different fuel types under three nozzle discharge angles are shown in Table 4.2 and they are plotted in Fig. 4.1 as well.

The extinction time curves can be divided into two types: one is the monotonic decreasing curve for diesel, and the others are the convex curves for gasoline and heptane, respectively. For diesel fuel, its narrower combustion limits and higher flash point make the curve different from the ones of gasoline and heptane. The extinction time decreases as the nozzle discharge angle increase for diesel, whereas it shows the contrary behaviors in the tests of gasoline and heptane. The worst performance of fire suppression occurs at the nozzle discharge angle of 45° that the extinction time is lowered no matter how the nozzle discharge angles increases or decreases. In the higher nozzle discharge angle regime (>45°), water mist is possible to fully cover the pan fire, so that the flame cooling and oxygen-displacement play the important roles. On the other hand, in the lower nozzle discharge angle (<45°) regime the mist jet rebounds from the pan wall and forms a thin mist layer parallel to fuel surface, thus blocks and dilutes the fuel vapors. So, it makes the fire extinction easier in the low nozzle discharge angle than that at 45°.

Figure 4.2(a)-(c) show the temperature variation histories of heptane, gasoline and diesel fires at the nozzle discharge angle of 30°. For the three fuel fires, the temperatures measured at 15*cm* above the fuel surface (i.e. thermocouple #3) in the flame center are the highest ones, which can reach as high as 650 to 750°C. After water mist is released, the flame size reduces quickly and is pushed back to ward the side wall of the pan, which is close to the nozzle. The fluctuations of temperatures at 0.5*cm* below the fuel surface (i.e. thermocouple #1) are almost invariant, whereas the temperatures measured at the fuel surface (i.e. thermocouple #2) and at 15*cm* and 30*cm* above the fuel surface (i.e. thermocouple #3 and #4) all rapidly decrease as the water mist is reached.

The tendencies of temperature of gasoline and heptane fires measured at thermocouple #2 are different from the diesel one. The former ones rapidly increase as water mist is discharged since the flame is pushed toward the fuel surface, and furthermore fresh air entrained with water mist flow enhances the burning of fuels. However, the temperature of diesel fire measured at #2 does not increase after water mist is released. Because the low vapor pressure and high flash point make diesel fuel hard to re-ignite after the fuel surface cooled by water mist.

In the case of gasoline fire, it is remarkable that the highest temperature can only reach to 550°C during the free burning, but after water mist is released, it can rise to 750°C. When gasoline fuel is burning, it produces a lot of smoke and the available oxygen is not enough after a certain period. Once water mist is released, the fresh air is entrained with water mist flow to enhance the burning of gasoline fuel. Therefore, combustion enhancement may be resulted from an improper design of the water mist fire extinguishing system.

Figure 4.3(a)-(c) are the radiation heat flux histories of heptane, gasoline and diesel fires at the nozzle discharge angle of 30°. The highest radiation heat fluxes that different fuel fires can reach are grouped into gasoline, heptane and diesel in descending order of their magnitudes. The result does correspond with their combustion heat. The radiation heat flux of fires rapidly reaches almost zero after the releasing of water mist. It shows that the water mist system has a good ability for radiation attenuation and can provide a good protection for the operators, who are using portable extinguishing equipment.

Figure 4.4 shows the oxygen concentration variation history in a gasoline fire for a demonstration. The oxygen mole concentration in air is about 20.9%, and after ignition, it gradually decreases to 14.4% since lots of smokes are produced during the initial burning. When the burning gradually reaches quasi-steady state, less smoke are produced. These result in a rise of oxygen concentration. When water mist is discharged, the fresh air is entrained with the flow so a large flare-up is generated in the moment. However, the measured oxygen concentration surge is not obvious. With continuous discharge of water, the evaporation of water mist brings a rapid clearance effect and reduces the oxygen concentration. Then the fire is pushed toward the fuel surface and its size becomes smaller so the oxygen concentration in the pan gradually rises again. After extinction, the oxygen concentration is back to 20.9%.

4.1.2 Water Mist with Additive on Diesel Pan Fires

Since diesel is hard to ignite due to its narrow combustion range and high flash point temperature (>52°C), an extra of 50*ml* gasoline, served as the accelerator, was provided. For ensuring the burnout of gasoline and reaching the quasi-steady burning, it took 120*s* of pre-burning before the water mist system activated. The extinction time for different additive solution volumes at three nozzle discharge angles are listed in Table 4.3. In the cases of fire suppression by using pure water, the best fire extinguishing performance was occurred at the nozzle discharge angle of 60° because mist could fully cover the pan fire. By using the water mist with additive, the fire extinguishing efficiency is found to improve. The best fire extinguishing efficiency occurs at 3% additive ones. However, if too much additive is provided, the fire extinguishment efficiency will decrease. Since the surfactant in additive not only has adverse effects on the atomization of water mist by increasing the surface tension but also can make the water mist more difficult to vaporize by increasing the boiling point. It does agree with the results of the experiments Zhou et al. [17] conducted. As shown in Fig. 4.4, the extinction time at three nozzle discharge angles were all significantly decreased comparing with those using pure water. There was an interesting phenomenon in these tests. When the nozzle discharge angle was at 30°, the more additive was added, the more time fire extinguishment needed. It shows that at the nozzle discharge angle of 30°, vaporizing effects of mist played a more important role in fire suppression than that of additive. However, the fire extinguishing time was still less than that using pure water.

4.1.3 Water Mist with Additive on Heptane Pan Fires

In the tests of heptane, its flame was turbulent but it didn’t produce a lot of smoke. At the beginning of the discharge, the flame height was reduced but the flame size became bigger than the initial one because the fresh air was entrained into the fire plume with water mist. Then, the flame expanded rapidly and stretched out concurrently with the continuous discharge. It was not easy to extinguish the heptane pan fires in the present tests. The extinction times for different additive solution volumes at three nozzle discharge angles were listed in Table 4.4 and they also were plotted in Fig. 4.6. There were two types of curves existed in the extinction time relationships; one was convex curves for the 0% and 3% additive, and the other was monotonic decreasing curve for 6% and 10% additive.

For the case of using water mist of 3% additive for fire suppression, the fire extinguishing time at the nozzle discharge angle of 30° was less than that at 45°. Because in the low nozzle discharge angle tests, the entrained flow rebounded from the pan wall and blocked the fuel vapor. When 3% additive was used, the fire extinguishing time was substantially reduced compared with 0% additive. However, the performance of fire suppression with low additive solution volume is similar to that with pure water. For the cases of 6% and 10% additive ones used in fire suppression, the lower the nozzle discharge angle was, the more the extinguishing time took. It is because that at the lower nozzle discharge angle, there was less mist being able to reach the fuel pan.

Figure 4.6 shows that at the nozzle discharge angle of 30°, the best performance of fire suppression occurs in the additive solution of 3%. The more the additive solution volumes increases, the more the fire extinguishing time. That is because that the vaporizing effect of mist plays a more important role than that of the additive in fire suppression at the nozzle discharge angle of 30°. When the nozzle discharge angle was increased to 60°, the trend was different. Firstly, the fire extinguishing time increased with the additive solution volume, which was less than 6%. When the additive solution volume was 6%, it took the longest time to extinguish the fire. After that, the fire extinguishing time decreased as the additive solution volume increased. This is because that the fire extinguishing efficiency is not only influenced by mist effects but also by additive ones. Therefore, there must exist an optimal zone between the mist and additive effects for fire suppression.

4.1.4 Water Mist with Additive on Gasoline Pan Fires

In the tests of gasoline, the turbulence of flame was quite intense and it produced a lot of smoke. The fire extinguishing behavior of gasoline was similar to that of heptane. The extinction time for different additive solution volumes at three nozzle discharge angles were listed in Table 4.5 and they were plotted in Fig. 4.7 as well. There were also two types of curves as a function of time existed, one was convex curves for

0% and 3% additive, and the other was monotonic decreasing curve for 6% and 10% of additive solution volume. The performance of fire suppression with low additive solution volume was similar to that with pure water. However, when additive was used, the fire extinguishing time were all obviously reduced as comparing with the one by using pure water. It was shown that the additive used in the present tests for fire suppression has a better performance for tackling gasoline fires than tackling heptane ones. Figure 4.7 shows that, at the nozzle discharge angle of 30°, the fire extinguishing time obviously decreases as the three additive solution volumes (3%, 6% and 10%) increases. It still reveals that vaporizing effects of mist are more important than additive ones at low nozzle discharge angle.

4.2 Tests with Different Amount of Fuels

In the cases of different amount of fuels in the pan, 250*ml*, 500*ml* and 1000*ml* of fuel were respectively contained in a circular stainless pan, with a diameter of 25*cm* and a height of 15*cm*, which was filled with 750*ml* water in advance. For the tests of diesel fuel, an extra of 50*ml* gasoline, served as the accelerator, was provided.

4.2.1 Pure Water Mist

In this section, pure water without additive was used as the fire suppression agent for tests with different amount of fuel. The following tests were performed with diesel and heptane fires at the nozzle discharge angle of 60°. The extinction time for pan fires with different quantities of diesel and heptane fuels are show in Table 4.6 and they are plotted in Fig. 4.8 as well. The extinction time curves for diesel and heptane fuels are obviously different. For heptane fires, the extinction time curve strongly depends on the amount of fuel, whereas the one for diesel is approximately independent of fuel quantities.

The free burning rates of diffusion flames do not become higher as the amount of fuel is increased in this case. The free burning rates of different amount of fuel in the fixed cross-section area of the pan are almost the same since they are related with the vaporizing rates of the fuel, which are further related with the cross-section area of the pan. On the other hand, the extinction time for different amount of water below the fixed amount of fuel are listed in Table 4.7. It shows that the amount of water does not affect the extinction time distinctly. The amount of fuel affects its thickness in the pan since the diameter of the pan was fixed in 25*cm*. The height of the liquid fuel is 0.5*cm*, 1.0*cm* and 2.0*cm* when the amount of fuel is 250*ml*, 500*ml* and 1000*ml*, respectively. The extinction time simply depends on the amount of fuel, thus the influence of total height of fuel and water on the results is ignorable when its range is between 1cm and 3.5cm.

In the case of diesel fires, the extinction time of 250*ml* is a little shorter than these of 500*ml* and 1000*ml*. It is remarkable that the burning rate of 250*ml* diesel is the lowest. When the amount of the fuel is 250*ml*, the 0.5*cm* thin layer of fuel film floats on the water surface will be pushed back to the side wall of the pan during the discharging of water mist. It makes the fuel surface non-uniform, and therefore slightly reduces the burning rate. When the height of liquid diesel is 1*cm*, the extinction time is quite close to the one for 2*cm*. It is evident that the situation of non-uniform liquid fuel surface can be ameliorated as the height of liquid diesel attains to 1*cm*.

In the tests of heptane, the extinction time is relative to the amount of fuel and their relationship is approximately linear, as shown in Fig. 4.8. The more heptane uses, the longer the extinction time takes. It is dissimilar to the diesel ones that the extinction time increases no more after the amount of fuel comes to 500*ml*. For heptane, it is hard to extinguish the fires directly with pure water. After water mist is discharged, the heptane should burn for a while to exhaust itself. The fire can not be extinguished until the heptane reduces to certain degree that water mist is able to perform its fire extinguishing ability. The characteristics of extinguishing heptane fires in theses cases tend to the almost running out of the fuel, and the pan is hard to reignite after extinction. The case of 500*ml* and 1000*ml* heptane are nearly two and four times of the extinction time for 250*ml* one. Thus the extinction time of heptane fire depends on the amount of fuel which is allowed for burning during the discharging of water mist.

4.2.2 Tests Using Water Mist with 3% Additive

In this section, water mist with 3% additive was used as the fire suppression agent for tests with different amount of fuel. The following tests were performed with diesel and heptane fires at the nozzle discharge angle of 60°. The extinction time for pan fires with different amount of diesel and heptane are shown in Table 4.10 and they are plotted in Fig. 4.9 as well. The fire extinguishing efficiencies for theses two fuel types are all significantly improved comparing with those using

0% additive.

For diesel fires, the extinction times for three different amount of fuel are short and very close to each other. The fires are all extinguished in 3*sec* after discharging, even if the amount of diesel is added to 1000*ml*. It shows that water mist with 3% additive is such an effective agent for diesel fires. Diesel itself is hard to ignite, because its low vapor pressure (2*mm*Hg) and high flash point (>52°C), and therefore is difficult to achieve its lower combustion limit. When additive is sprayed out from the nozzle, it is able to cool the diesel and form a thin layer of foamy film on the diesel surface. The foamy film makes the diesel fuel harder to ignite since it isolates the oxygen and blocks the diesel vapors. Thus water mist with 3% additive is quite effective for tackling diesel fires.

For heptane fires with 3% additive, the extinction time is much shorter than those using 0% additive. The best fire extinguishing performance occurs at the amount of heptane of 250*ml* that its height is 0.5*cm* hence the fuel surface become non-uniform after discharging. When the amount of heptane attains to 500*ml* that its height is 1*cm*, the situation of non-uniform liquid fuel surface can no longer take place. The extinction times for fire tests with 500 and 1000*ml* heptane are quite close, and apparently are not influenced by the height of liquid fuel because the situation of non-uniform liquid fuel surface do not happen anymore.

4.2.3 Tests with 2cm Height of the Liquid Fuel

Since the situation of non-uniform liquid fuel surface does not occur as the amount of fuel is 1000*ml*, the following efforts in this section are conducted with 1000*ml* heptane for comparing with the results of the previous section 4.1.3, “Water Mist with Additive on Heptane pan Fires”, which is conducted with 250*ml* heptane. The extinction times of heptane fires with different height of liquid fuel for different additive solution volumes at three nozzle discharge angle are listed in Table 4.9 and they also are plotted in Fig. 4.10.

For the cases of using 0% and 3% additive, there are still two convex curves for the extinction time relationships like the results in section 4.1.3. The fire extinguishing efficiencies are both reduced as the amount of heptane is added to 1000*ml*. The extinction time for the cases of using 0% additive is especially affected, and it is almost four times of the extinction time for 250*ml* one. It is because 0% additive is not able to put out heptane fires with 1000*ml* fuel while the situation of non-uniform liquid fuel surface does not occur.

Figure 4.11 shows the temperature variation history for pure water. In the free burning conditions, the temperature measured at 15*cm* above the fuel surface (i.e. thermocouple #3) in the flame center is the highest one, which can reach approximately 750°C. After water mist is continuously discharged, the flame is pushed toward the fuel surface and its height is reduced so that the temperatures measured at thermocouple #3 and #4 are reduced. However, the reduction of flame height and the fresh air entrainment increase the convection between the flame and the fuel, and then resulting in an increase of fuel burning rate in the region of thermocouple #2. Figure 4.12 is the radiation heat flux history. Since 0% additive is not able to put out heptane fires, the radiation heat flux from the fire remains existent after water mist is discharged, but its magnitude obviously reduced. The extinction times in theses cases tend to the almost consumption of fuel, and the pan is hard to reignite after extinction as well. However, the tendencies of the fire extinction time do agree with those results of section 4.1.3.

For the cases of 6% and 10% additive ones used in fire suppression, the lower the nozzle discharge angle is, the more the extinguishing time take. The results quite agree with those, which are conducted with 250*ml* of heptane. Besides, the extinction times for 250 and 1000*ml* of heptane fuel are close. It is because that the extinction times for 6% and 10% additive ones depend on the duration which foamy film fully covers the whole heptane fuel surface. Therefore, no mater how the amount of fuel is, the fire extinguishing efficiency remains fixed.

4.3 Tests with Different Cross-Section Area of Pan

In this section, the pan area effect is investigated with a circular stainless pan, with a diameter of 50*cm* and a height of 15*cm*, for comparing with the results in the previous section 4.1.3, which are conducted with a circular stainless pan, with a diameter of 25*cm* and a height of 15*cm*. For the tests with a diameter of 50*cm*, 2000*ml* of water and 1000*ml* of heptane were filled. Both height of the heptane fuel in the two pans with different cross-section area are 0.5*cm*. The extinction times of heptane fires with different cross-section area of pan for different additive solution volumes at three nozzle discharge angle are listed in Table 4.10 and they also are plotted in Fig. 4.13.

In the case of using 0% additive, the fires are too big to be suppressed. The extinction time for three discharge angles are the duration of running out of the fuel, and the pan is not able to reignite after extinction. The pan fires with a diameter of 50*cm* are much bigger than those with a diameter of 25*cm*. Besides, the mist is not enough to cover the whole pan. So the fire extinguishing efficiency is greatly reduced.

Figure 4.14 shows the temperature variation history. In the free burning conditions, the temperature measured at 30*cm* above the fuel surface (i.e. thermocouple #4) reached approximately 800°C and tended to be maintained steaily after a certain period. However, the temperature measured at the fuel surface (i.e. thermocouple #2) reaches to approximately 530°C and then decreases, because the fresh air is difficult to reach this region which is located at 14*cm* below the top edge of the pan. After water mist is released at 80th second, the temperatures measured at thermocouple #4 and #3 rapidly reduce to approximately 650°C, but the flame size is still large. Since the fresh air is entrained into the fire plume and it increases the oxygen supply to the combustion after water mist is discharged, the temperature measured at thermocouple #2 increased. The above results for the temperature variation history of heptane fires are quite similar to the ones of Liu et al. [16]. Figure 4.15 is the radiation heat flux history. The radiation heat flux of fires drastically reduces after the releasing of water mist, although the fires are still large. It shows that water mist system has an effective ability for radiation attenuation. Since using 0% additive can not suppress the fires in such pan scale, and the effect of mist jet rebounds from the pan wall is no longer significant, it is remarkable that the fire extinction time gets shorter as the nozzle discharge angle decreases. The more the nozzle discharge angle is, the better the ability to damp down fires, hence the highest burning rates occurs at the lowest nozzle discharge angle. In other words, it takes the shortest time to run out of the fuel at the nozzle discharge angle of 30°.

For using water mist with additive, the results of experiments at the nozzle discharge angle of 45° and 60° are similar to those with a diameter of 25*cm*. However, at the nozzle discharge angle of 30°, the fire extinguishing efficiency is worse for the cases of 3% additive, but it is better for 6% and 10% ones. As mentioned in section 4.1.3, at the nozzle discharge angle of 30°, for the cases of 3% additive, vaporizing effects of mist played a more important role in fire suppression than that of additive. On the contrary, for the cases of 6% and 10% ones, additive effects are more important. From a geometric perspective, in the cases of pan with diameter of 50*cm* and at nozzle discharge angle of 30°, there is less ability for mist jet to rebound from the pan wall and form a thin mist layer parallel to fuel surface. So the fire extinguishing efficiency is worse for the cases of 3% additive. Besides, there is more mist being able to reach the fuel pan, and therefore it has a better fire extinguishing efficiency for the cases of 6% and 10% additive ones. Thus at nozzle discharge angle of 30°, the interactions of poorer mist coverage, weaker mist jet rebound and more mist reaching make there exists discrepancies between the results of this section and section 4.1.3.

CHAPTER 5
CONCLUSIONS

In this study, the effects of discharge methodologies on the pool fire extinguishment performance of portable high pressure water mist extinguishing system with additive and the corresponding mechanisms of restraining fire are studied. The additive added in water mist is neither toxic nor corrosive. All the tests are regarded as fuel-controlled. The test parameters include the fuel type, nozzle discharge angle, additive solution volume, amount of fuel, and cross-section area of pan. The fuels used are heptane, gasoline, and diesel, the nozzle discharge angles are 30°, 45°, and 60° with respect to the horizon, and the additive solution volumes are 0%, 3%, 6% and 10%. The amounts of fuel used are 250*ml*, 500*ml* and 1000*ml*, and the diameters of pan are 25*cm* and 50*cm*.

For all types of pool fires, the test results by using pure water mist show that the flame cooling and oxygen-displacement play the important roles in the higher nozzle discharge angle regime (>45°). In the lower one (<45°), the blocking and dilution of fuel vapors at interface are the dominant factors. Besides, the water mist system has a good ability for radiation attenuation and temperature reduction that can provide a good protection for the operators, who are using portable extinguishing equipment.

For the tests with different fuels, the fire extinguishing behaviors of diesel are different from the ones of heptane and gasoline. For diesel fires, the fire extinguishing efficiencies using the water mist with additive at three nozzle discharge angles are all significantly improved comparing with those using pure water. However, if too much additive is provided, the fire extinguishment efficiency will decrease. For heptane and gasoline fires, the performance of fire suppression with 3% additive solution volume is similar to those with pure water, and for the 6% and 10% additive ones, the lower the nozzle discharge angle is, the more the extinguishing time spends since there is less mist being able to reach the fuel surface.

The test results with different amount of fuels in a size-fixed pan show that the non-uniform fuel surface resulted from water mist impingement slightly reduces the burning rate. The situation of non-uniform liquid fuel surface can be ameliorated as the height of liquid fuel attains at 1*cm*. However, the tendencies of the fire extinction times for different amount of fuel are similar.

In the tests with different cross-section area of pans, which are in the fixed fuel height, the interactions of poorer mist coverage, weaker mist jet rebound and more mist reaching make the results of 50*cm* diameter pan different to the ones of 25*cm* diameter, especially at nozzle discharge angle of 30°. The fire extinguishing efficiency is not only influenced by mist effects but also by additive ones. Therefore, there must be an optimal mixing ration between the mist and additive for fire suppression.

Finally, there are some suggestions for the extensions of the present experiments. The mean droplet size of the discharging water can be measured by the particle image velocity (PIV) system to confirm whether the droplets meet with the standard of mist. Installing the Gaseous Oxygen Analyzer used to measure the oxygen variation histories in fire during tests is beneficial to analyze the mechanisms of fire extinction. Based on the results of fire extinguishing performance on pool fires in this study, it is worthy to practice them in actual applications, such as semiconductor wet benches. Moreover, the interactions of fire extinguishing parameters in the full-scale fire tests are usually complicated. By using computational simulations to verify and compare with the results of experiments, would make the evaluation process more logical and accurate.

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Table 2.1 The properties of fuels

Properties	Fuel types		
	Heptane	Gasoline	Diesel
Boiling point (°C)	98	30~210	163~357
Density (kg/m^3)	675	720~760	876
Flash point (°C)	-4	-43~-38	>52
Auto-ignition point (°C)	104	280~456	103
Lower Explosive Limit (%)	1.07	1.2~1.4	1.3
Vapor Pressure (mmHg)	40	259~777	2
Heat of combustion (MJ/kg)	44.6	47	42.4

Table 2.2 The volume flow rates of mist in different additive solution volumes (L/min)

Additive solution volume	0%	3%	6%	10%
Volume flow rate	8.8	9.0	9.0	8.8

Table 3.1 The table of experimental repeatability (a) Pure water tests with different fuel types in 25cm diameter of the pan (b) Water mist with additive in 50cm diameter of the pan with heptane fires

(a)

Nozzle discharge angle	The extinction time for Heptane (s)				
	1st	2nd	3rd	Average	C.V.
60°	76	88	80	81	6.13%
45°	111	100	105	105	4.33%
30°	79	79	77	78	1.20%

Nozzle discharge angle	The extinction time for Gasoline (s)				
	1st	2nd	3rd	Average	C.V.
60°	90	87	91	89	1.90%
45°	156*	152*	152*	153*	1.23%
30°	97	113	112	107	6.82%

Nozzle discharge angle	The extinction time for Diesel (s)				
	1st	2nd	3rd	Average	C.V.
60°	8	7	7	7	6.43%
45°	56	52	55	54	3.13%
30°	64	64	58	62	4.56%

(b)

Nozzle discharge angle	The extinction time for water mist with 0% additive (s)				
	1st	2nd	3rd	Average	C.V.
60°	114	108	110	111	2.25%
45°	84	74	78	78	3.69%
30°	47	47	55	50	7.54%

Nozzle discharge angle	The extinction time for water mist with 3% additive (s)				
	1st	2nd	3rd	Average	C.V.
60°	18	18	17	18	2.67%
45°	35	37	35	36	2.64%
30°	50	47	51	49	3.45%

Nozzle discharge angle	The extinction time for water mist with 6% additive (s)				
	1st	2nd	3rd	Average	C.V.
60°	25	25	23	24	3.87%
45°	43	39	42	41	4.11%
30°	23	27	23	24	7.75%

Nozzle discharge angle	The extinction time for water mist with 10% additive (s)				
	1st	2nd	3rd	Average	C.V.
60°	23	22	24	23	3.55%
45°	45	47	50	47	4.34%
30°	25	22	24	24	5.27%

Table 4.1 The summary of parametric studies

Variables	Range
Fuel types	Heptane, Gasoline, Diesel
Additive solution volume	0%, 3%, 6% and 10%
Nozzle discharge angle	30°, 45° and 30°
Amount of fuel (*ml*)	250, 500 and 1000
Diameter of the pan (*cm*)	25 and 50

Table 4.2 Nozzle discharge angle and corresponding extinction time(sec) without additive

Pure Water without Additive			
Fuel type Discharge angle	Diesel	Gasoline	Heptane
60°	8	89	82
45°	54	154	106
30°	59	106	79

(Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

Table 4.3 Corresponding extinction time(sec) of diesel fires

Diesel				
Additive Discharge angle	0%	3%	6%	10%
60°	8	3	5	8
45°	54	9	19	10
30°	59	3	25	38

(Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

Table 4.4 Corresponding extinction time(sec) of heptane fires

Heptane				
Additive Discharge angle	0%	3%	6%	10%
60°	81	18	28	18
45°	105	58	36	37
30°	78	17	77	79

(Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

Table 4.5 Corresponding extinction time(sec) of gasoline fires

Gasoline				
Additive Discharge angle	0%	3%	6%	10%
60°	89	9	15	9
45°	154	26	15	14
30°	106	9	34	54

(Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

Table 4.6 Amount of fuel and corresponding extinction time (sec) at the nozzle discharge angle of 60° with 0% additive

Fuel types Amount of fuel	Diesel	Heptane
250*ml*	10	80
500*ml*	14	174
1000*ml*	14	341

(Diameter of pan: 25*cm*, Amount of water below fuels: 750*ml*)

Table 4.7 Amount of water below heptane fuel and corresponding extinction time(sec)

250*ml* heptane fuel	
Amount of water below fuels	Extinction time
750ml	80
1000ml	84
1500ml	82

(Diameter of pan: 25*cm*, Nozzle discahrge angle: 60°, Additive solution volume: 0%)

Table 4.8 Amount of fuel and corresponding extinction time (sec) at the nozzle discharge angle of 60° with 3% additive

Fuel types Amount of fuel	Diesel	Heptane
250ml	3	20
500ml	3	34
1000ml	3	32

(Diameter of pan: 25*cm*, Amount of water below fuels: 750*ml*)

Table 4.9 Corresponding extinction time(sec) of Heptane fires with different height of liquid fuel

	0.5*cm* height of heptane				2*cm* height of heptane			
Additive Discharge angle	0%	3%	6%	10%	0%	3%	6%	10%
60°	81	18	28	18	342	30	29	14
45°	105	58	36	37	383	68	37	36
30°	78	17	77	79	312	23	86	87

(Diameter of pan: 25*cm*)

Table 4.10 Corresponding extinction time(sec) of Heptane fires with different cross-section area of pan

	25*cm* Diameter of the pan				50*cm* Diameter of the pan			
Additive Discharge angle	0%	3%	6%	10%	0%	3%	6%	10%
60°	81	18	28	18	111	18	24	23
45°	105	58	36	37	78	36	41	47
30°	78	17	77	79	50	49	24	24

(Height of liquid fuel: 0.5*cm*)

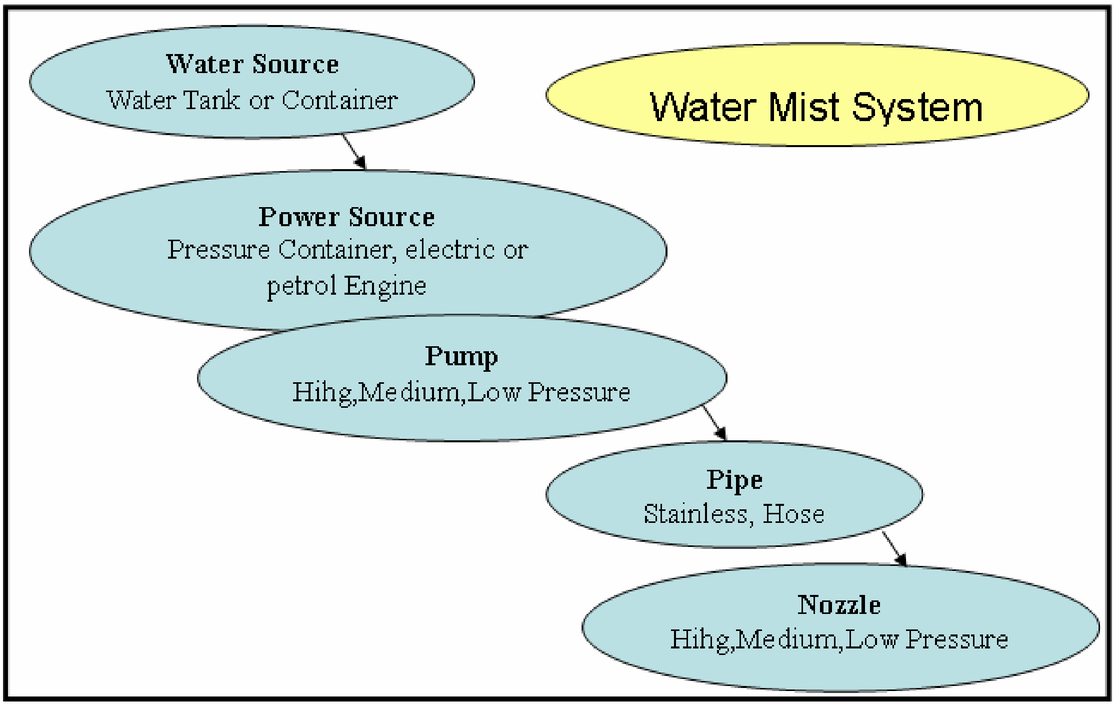


Fig. 1.1 Operation units of water mist system

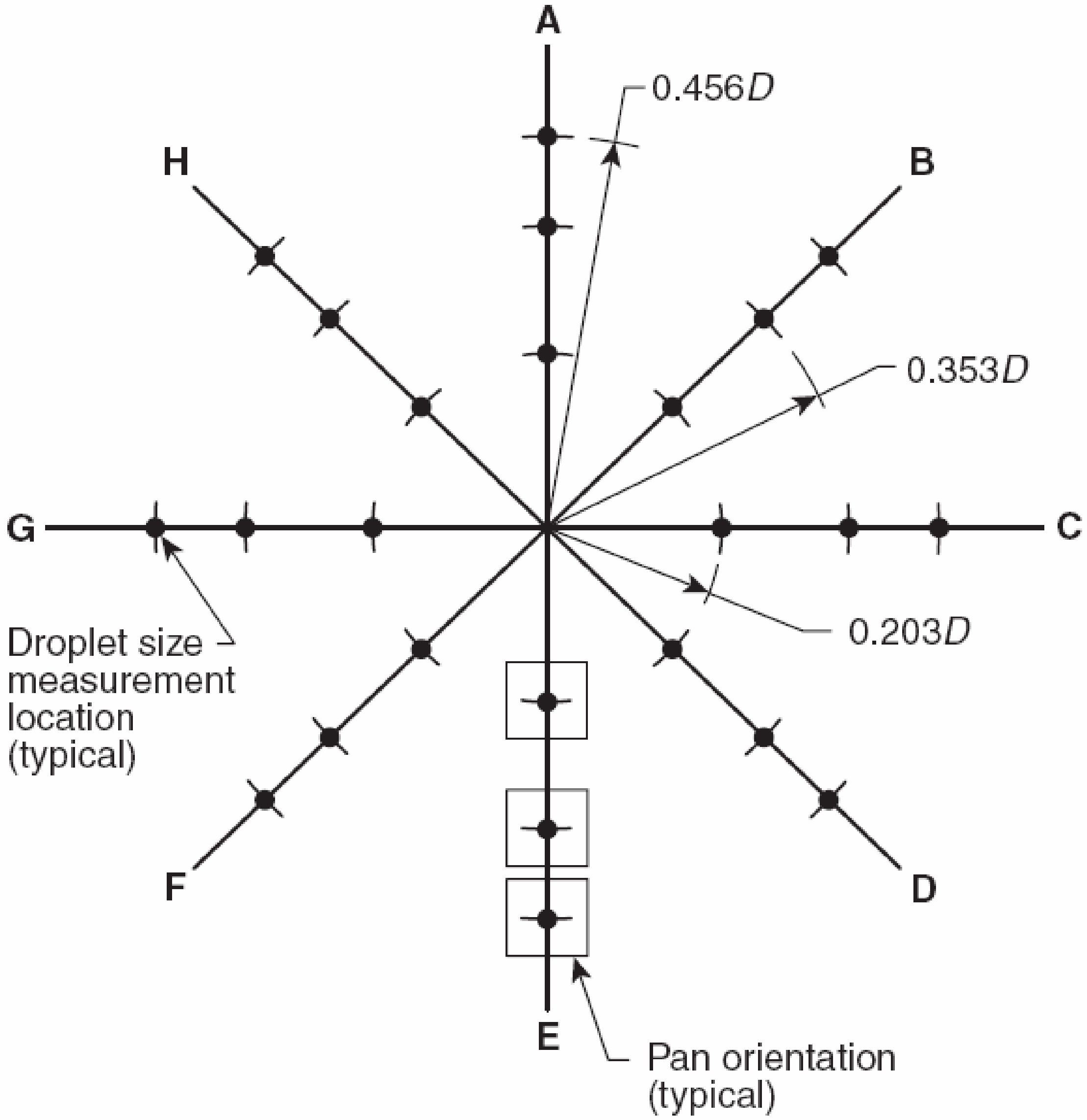


Fig. 1.2 Droplet size measurement locations [1] Reproduced from NFPA 750, “Standard for the Installation of Water Mist Fire Protection Systems”

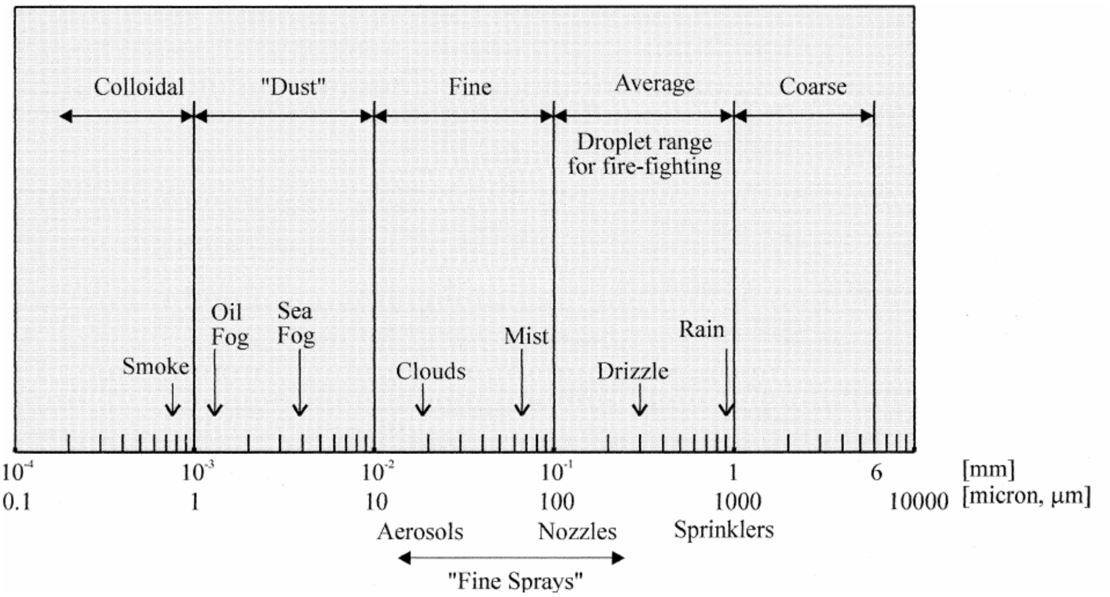


Fig. 1.3 Spectrum of droplet diameters, reproduced from Ref. [6]

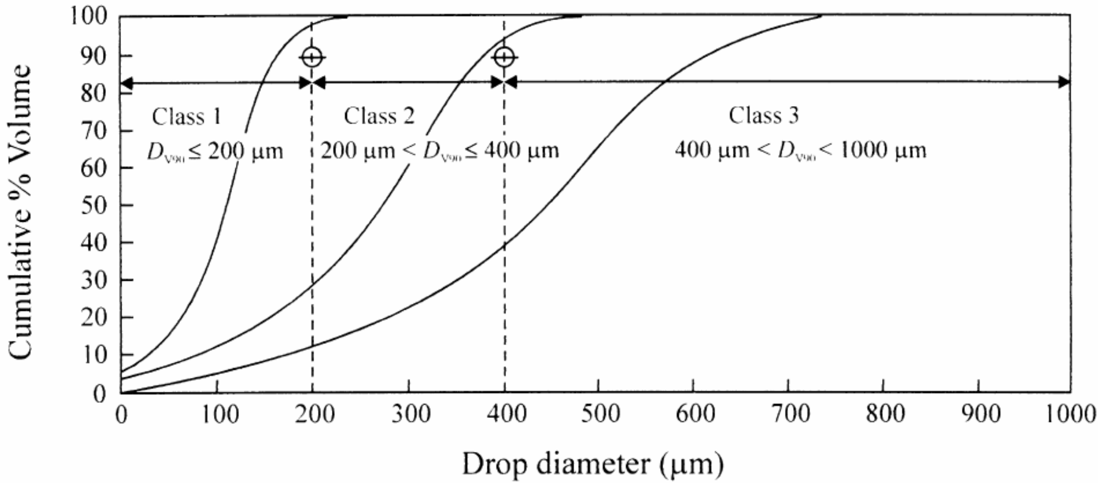


Fig. 1.4 Droplet diameters, reproduced from Ref. [7]

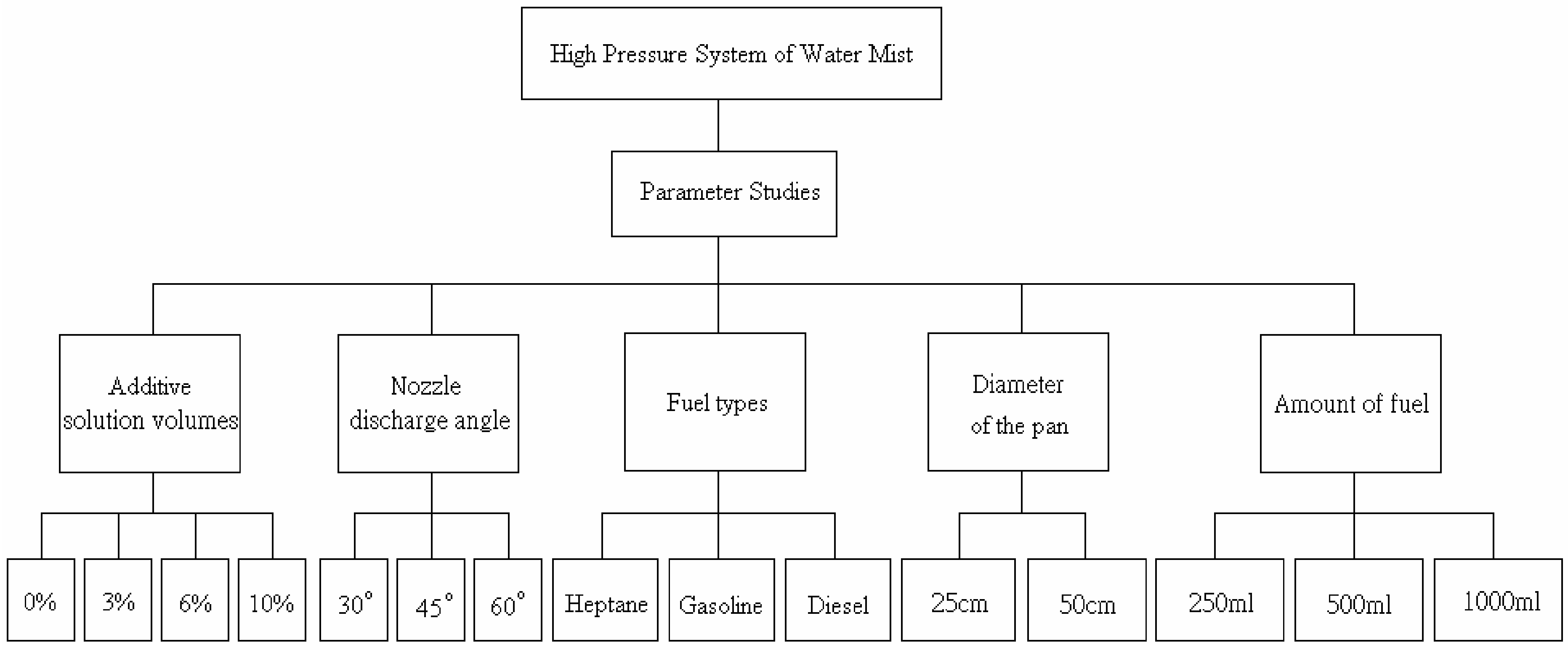


Fig. 1.5 Scheme diagram of the thesis

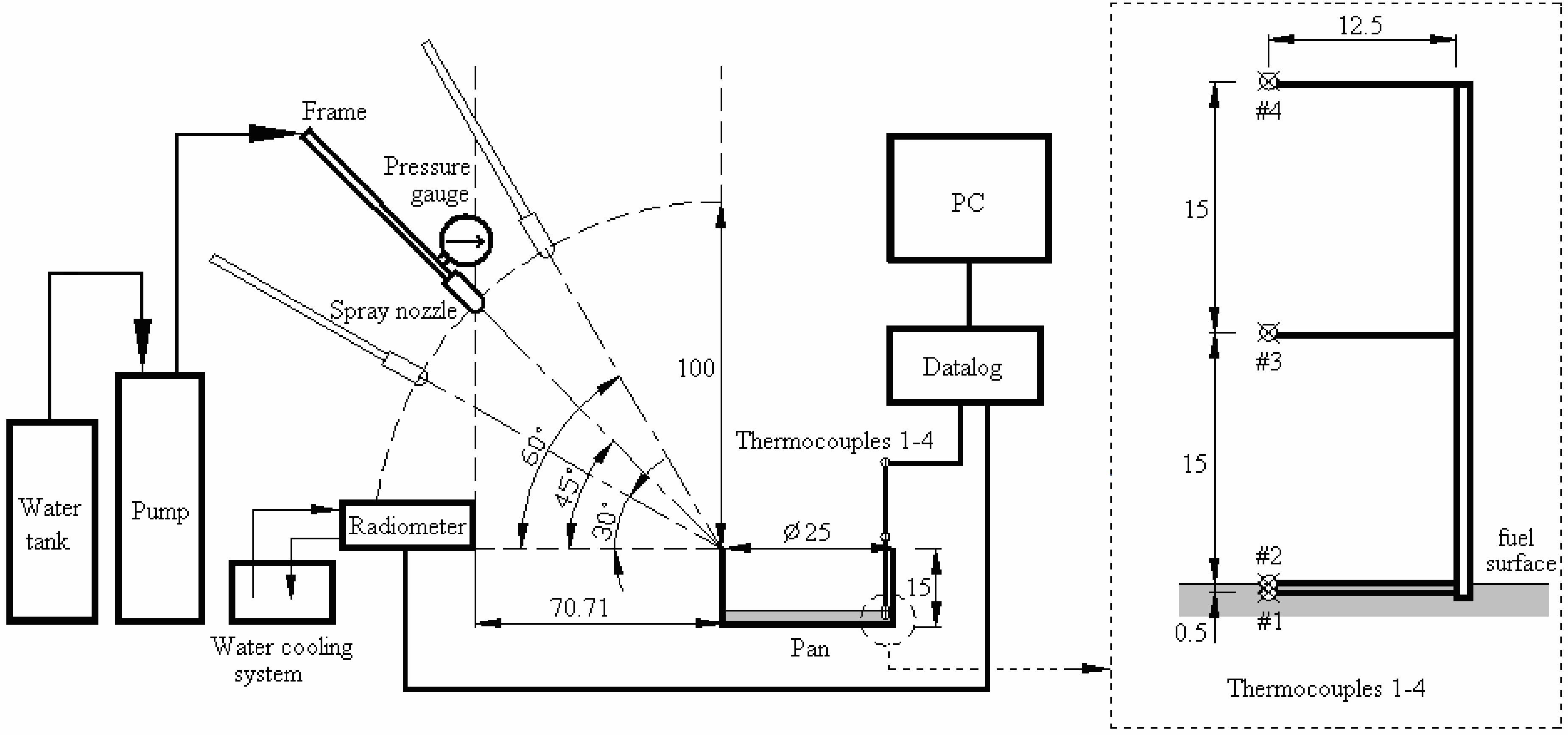
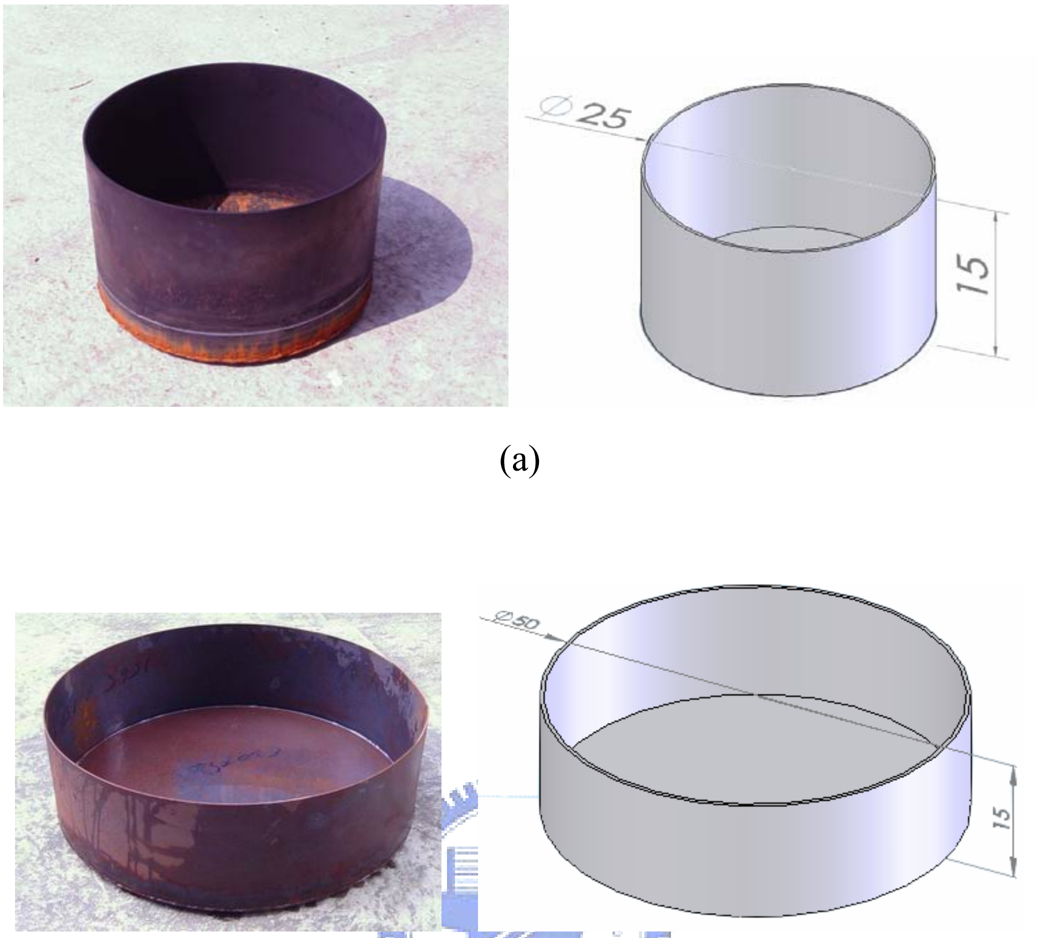


Fig. 2.1 The schematic configuration of the experimental apparatus (dimensions are in centimeters)



(a)

(b)

Fig. 2.2 The picture and schematic configuration of the circular stainless pan (a) small-scale (b) middle-scale (dimensions are in centimeters)

Fig. 2.3 The picture of high pressure pump

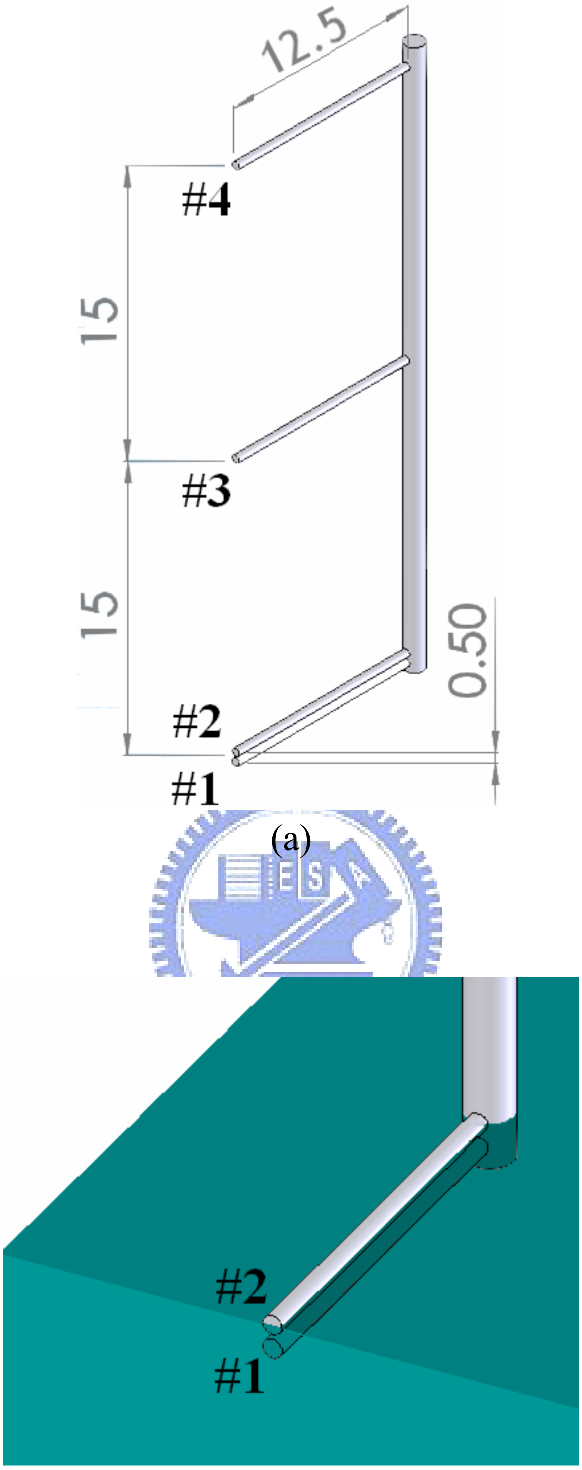
(a)

(b)

(c)

Fig. 2.4 The picture of high pressure system nozzle (a) Front view (b) Side view (c) Spray angle

Fig. 2.5 The picture of thermocouple tree

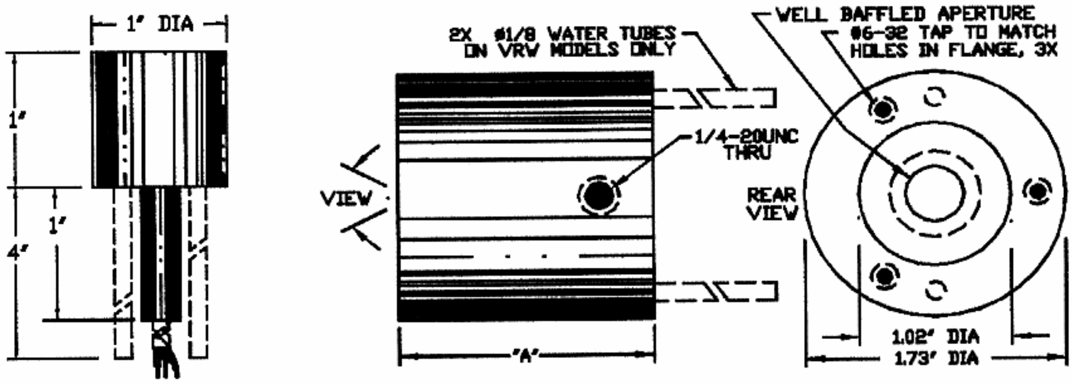


(a)

(b)

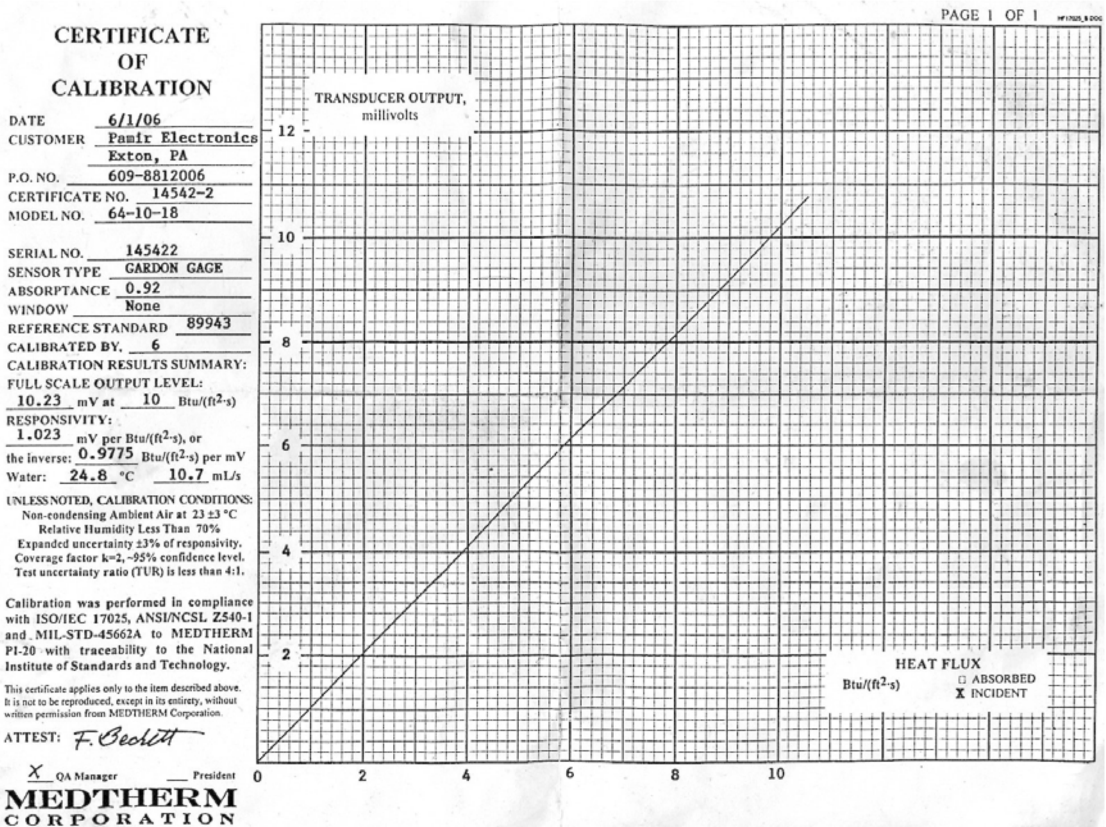
Fig. 2.6 The schematic configuration of the thermocouple tree (a) Whole view and (b) Local view (dimensions are in centimeters)

(a)



(b)

Fig. 2.7 The radiometer (a) The picture and (b) The schematic configuration



PAGE 1 OF 1

CERTIFICATE
OF
CALIBRATION

DATE 6/1/06
CUSTOMER Pamir Electronics
Exton, PA
P.O. NO. 609-8812006
CERTIFICATE NO. 14542-2
MODEL NO. 64-10-18

SERIAL NO. 145422
SENSOR TYPE GARDON GAGE
ABSORPTANCE 0.92
WINDOW None
REFERENCE STANDARD 89943
CALIBRATED BY. 6
CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
10.23 mV at 10 Btu/(ft^2·s)
RESPONSIVITY:
1.023 mV per Btu/(ft^2·s), or
the inverse: 0.9775 Btu/(ft^2·s) per mV
Water: 24.8 °C 10.7 mL/s

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

This certificate applies only to the item described above. It is not to be reproduced, except in its entirety, without written permission from MEDTHERM Corporation.

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Fig. 2.8 The certificate of calibration of the radiometer

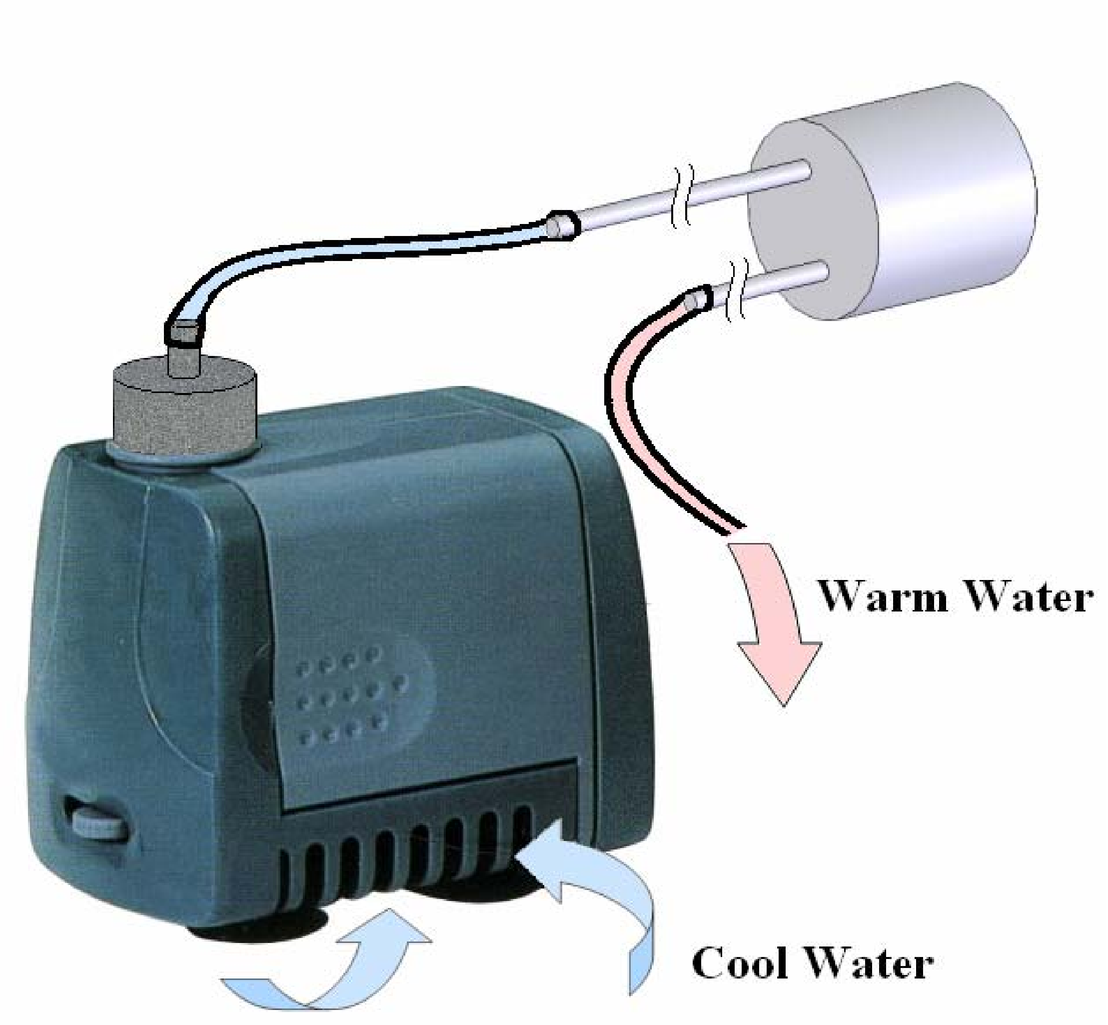


Fig. 2.9 The schematic configuration of the water-cooling system

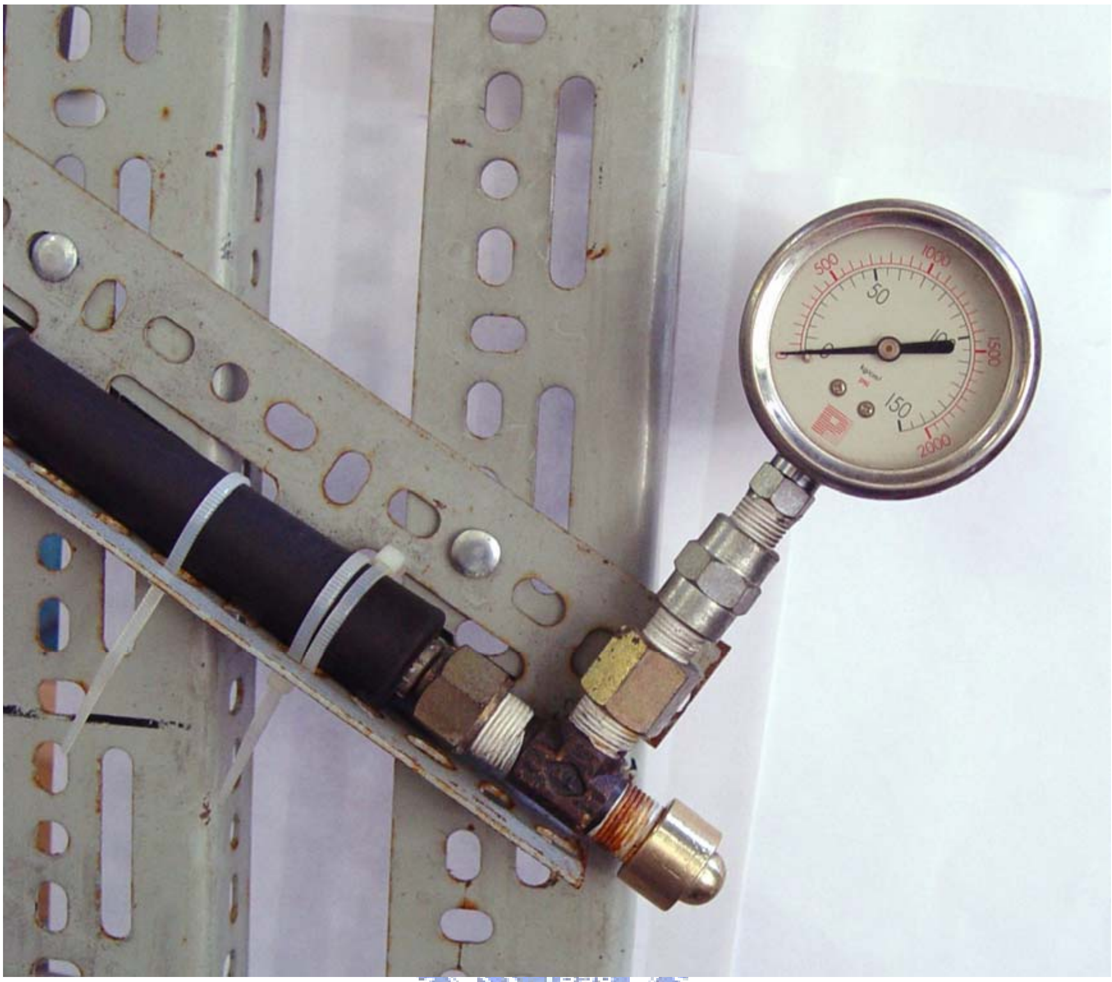


Fig. 2.10 The picture of pressure gauge

Fig. 2.11　The picture of Gaseous Oxygen Analyzer

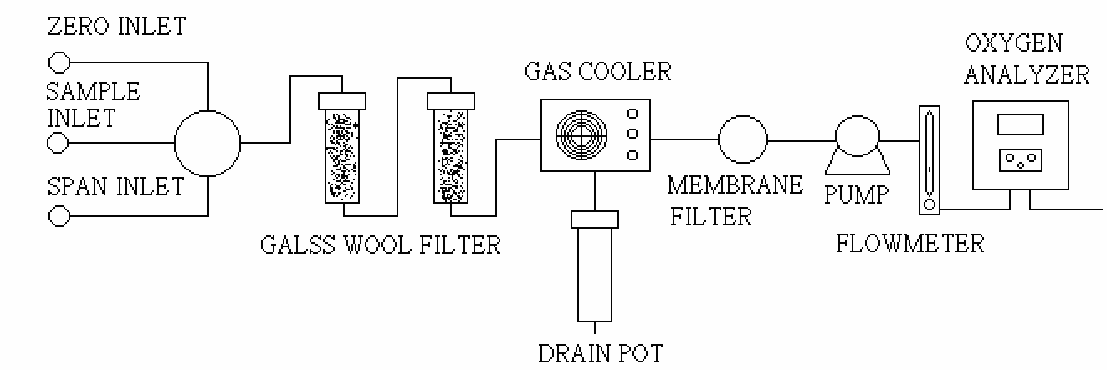
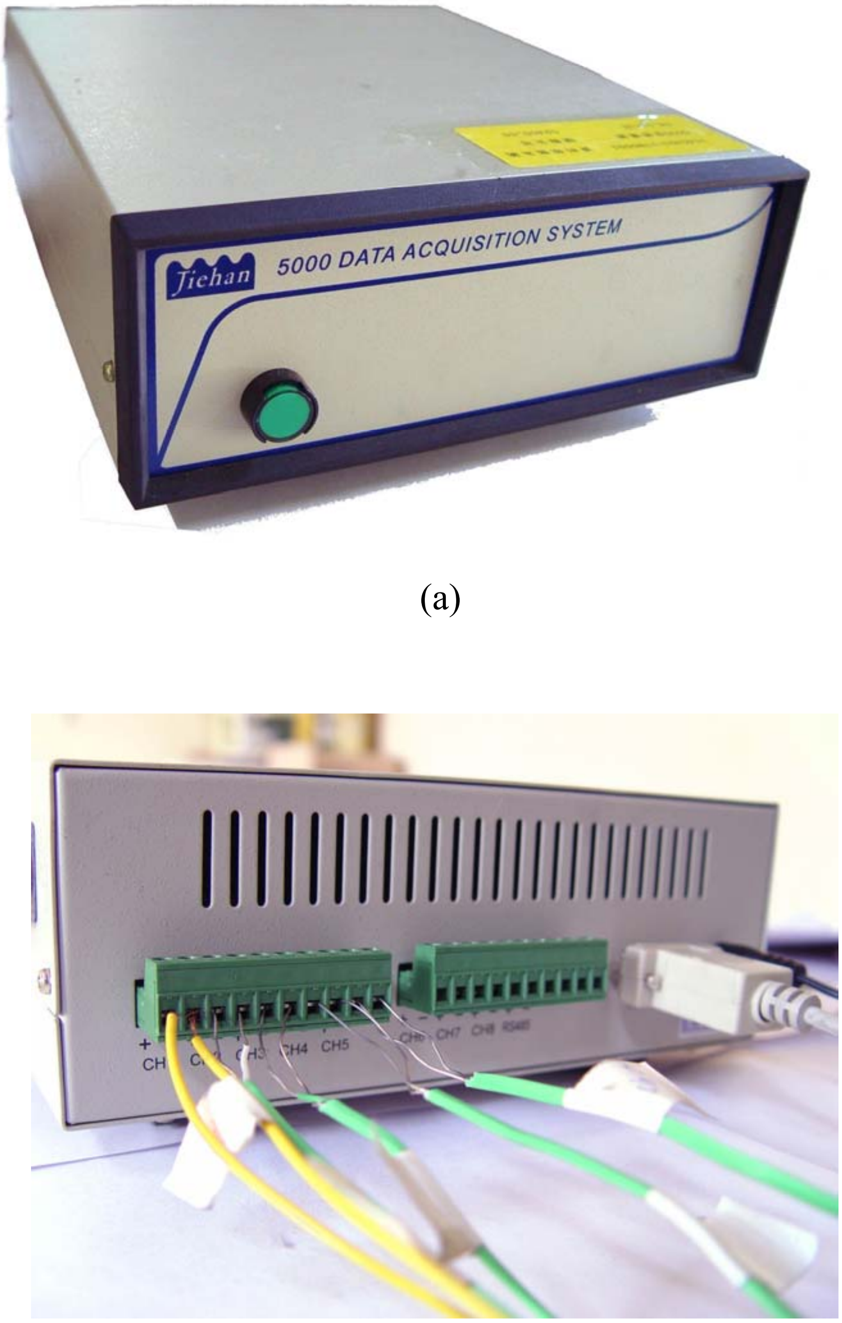


Fig. 2.12　Schematic configuration of preliminary handling system



(a)

(b)

Fig. 2.13 The picture of datalog (a) Front view and (b) Back view

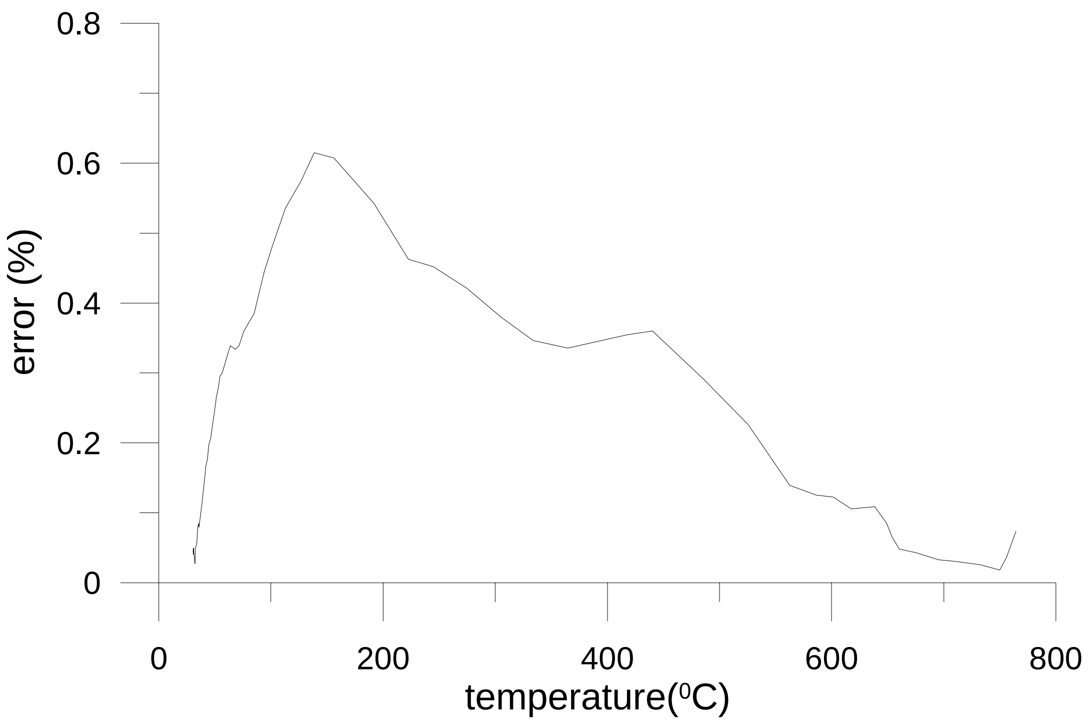
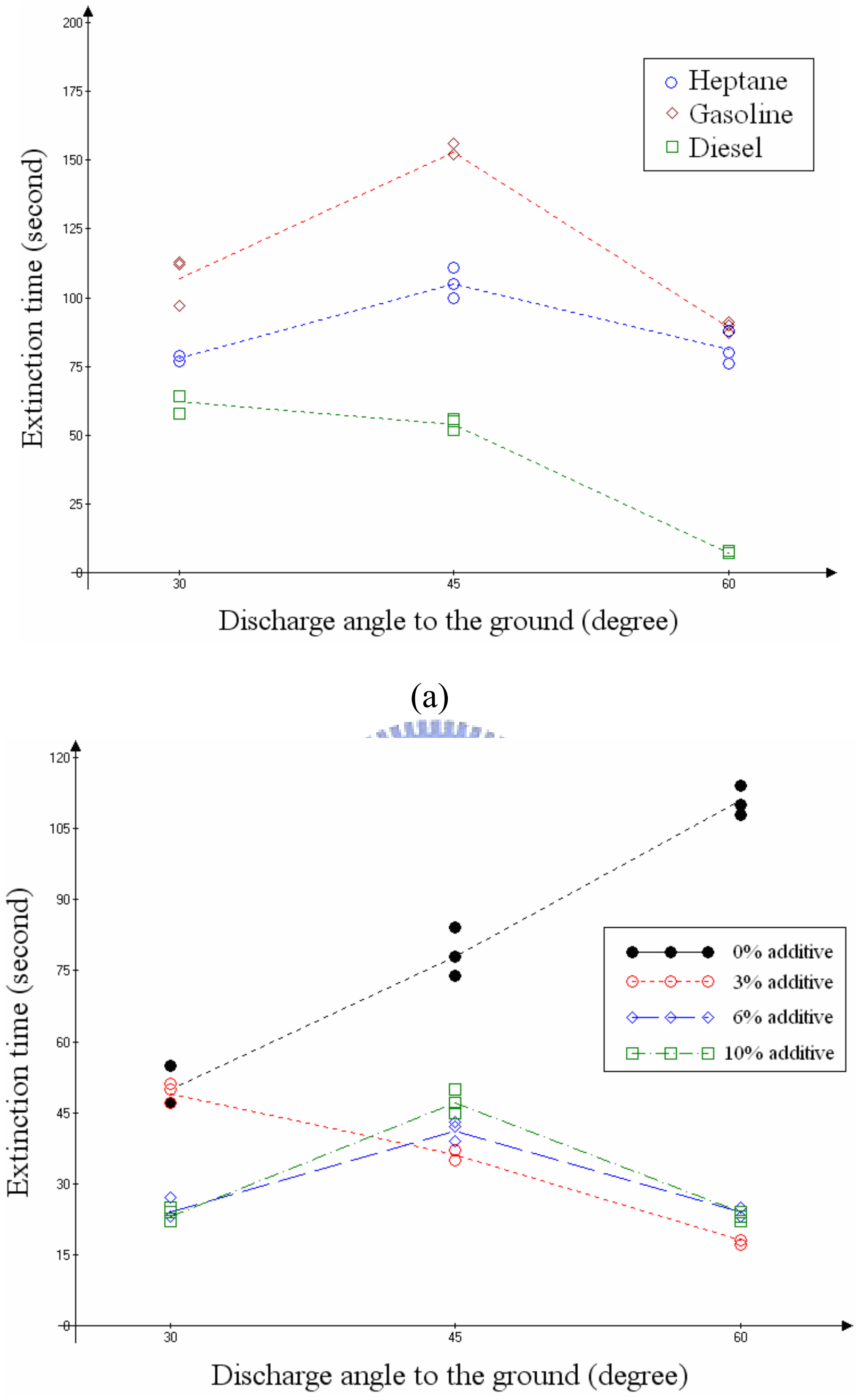


Fig. 3.1 The relationship of temperature and error, reproduced from Ref. [30]



(a)

(b)

Fig. 3.2 The diagram of experimental repeatability (a) Pure water tests with different fuel types in 25cm diameter of the pan (b) Water mist with additive in 50cm diameter of the pan with heptane fires

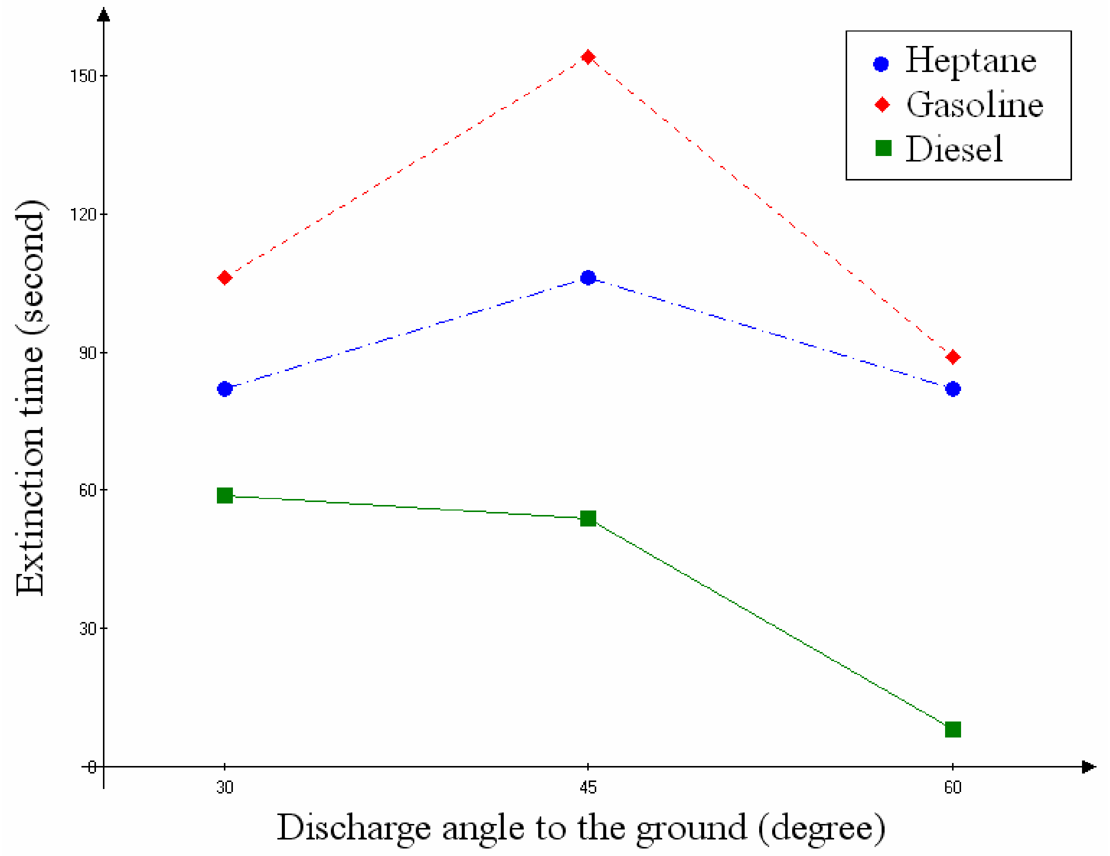
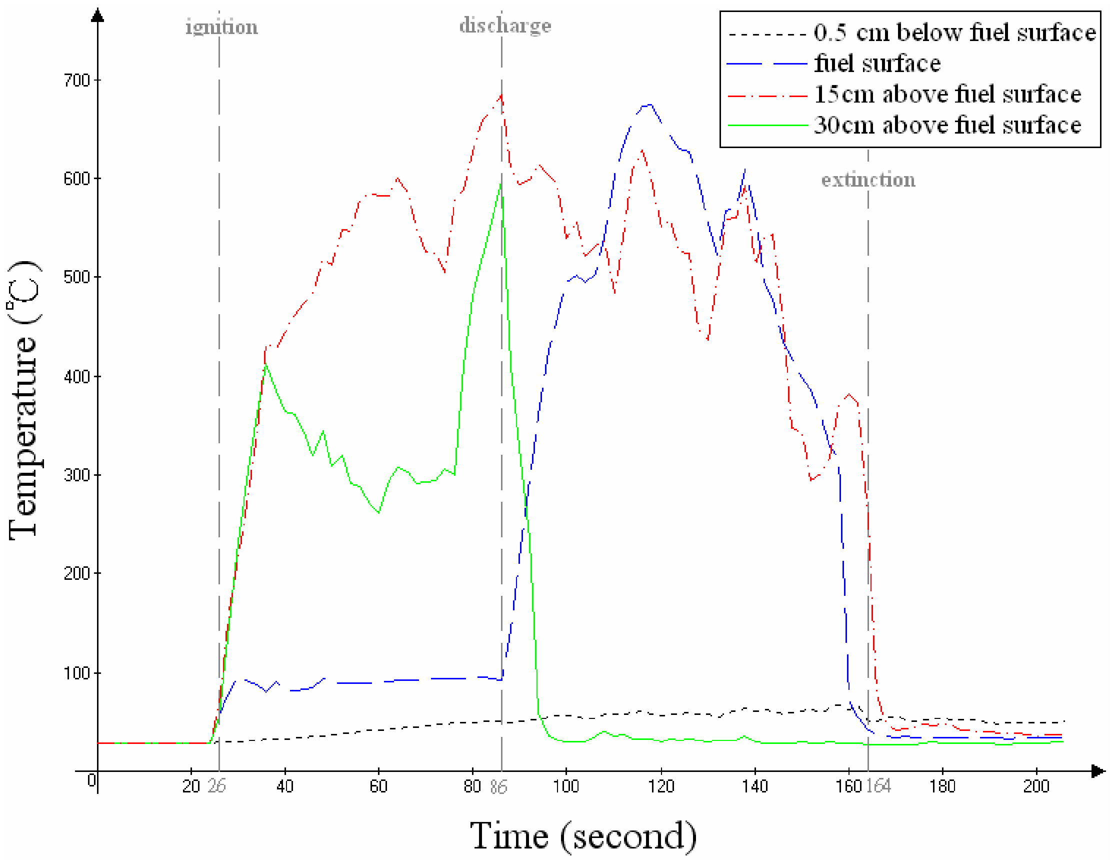
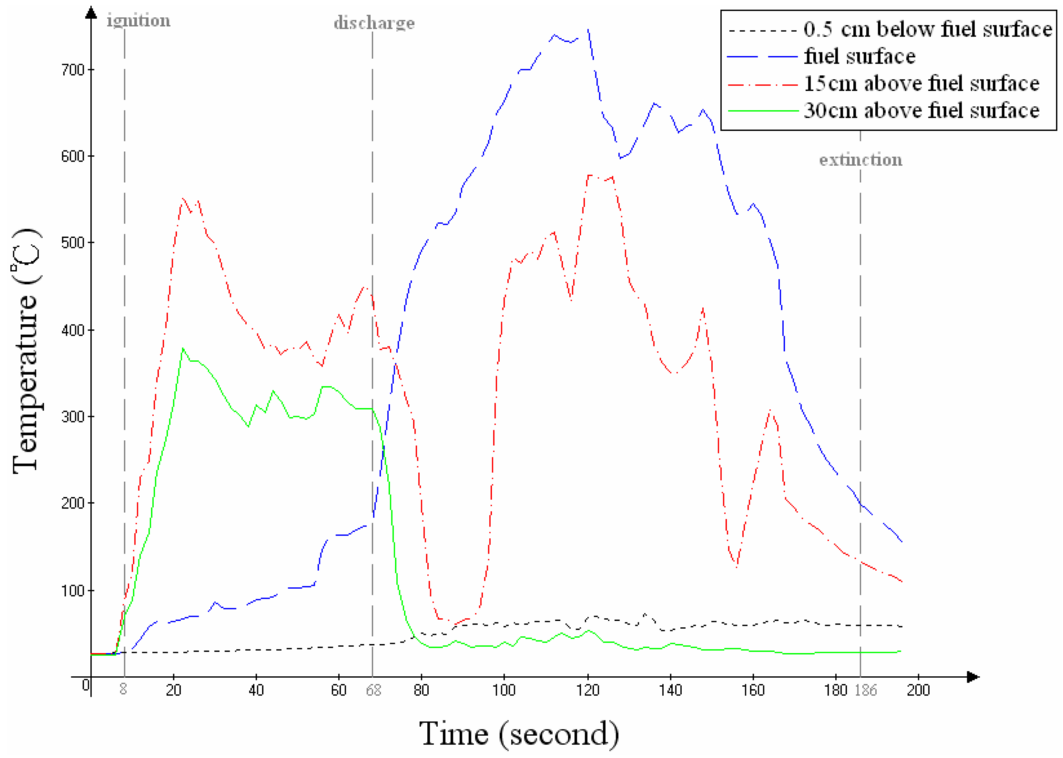


Fig. 4.1 The relationship between nozzle discharge angles and extinction time in different fuel types without addtive (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

(a) Heptane



(b) Gasoline



(c) Diesel

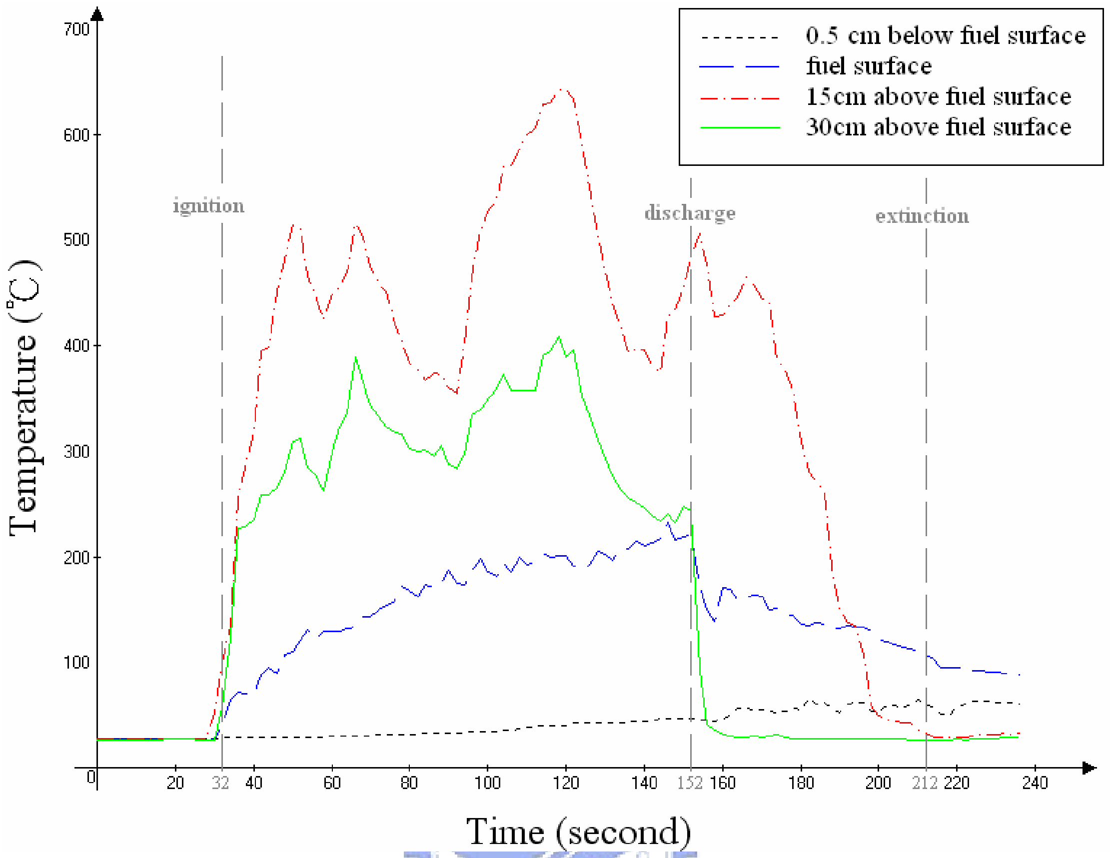
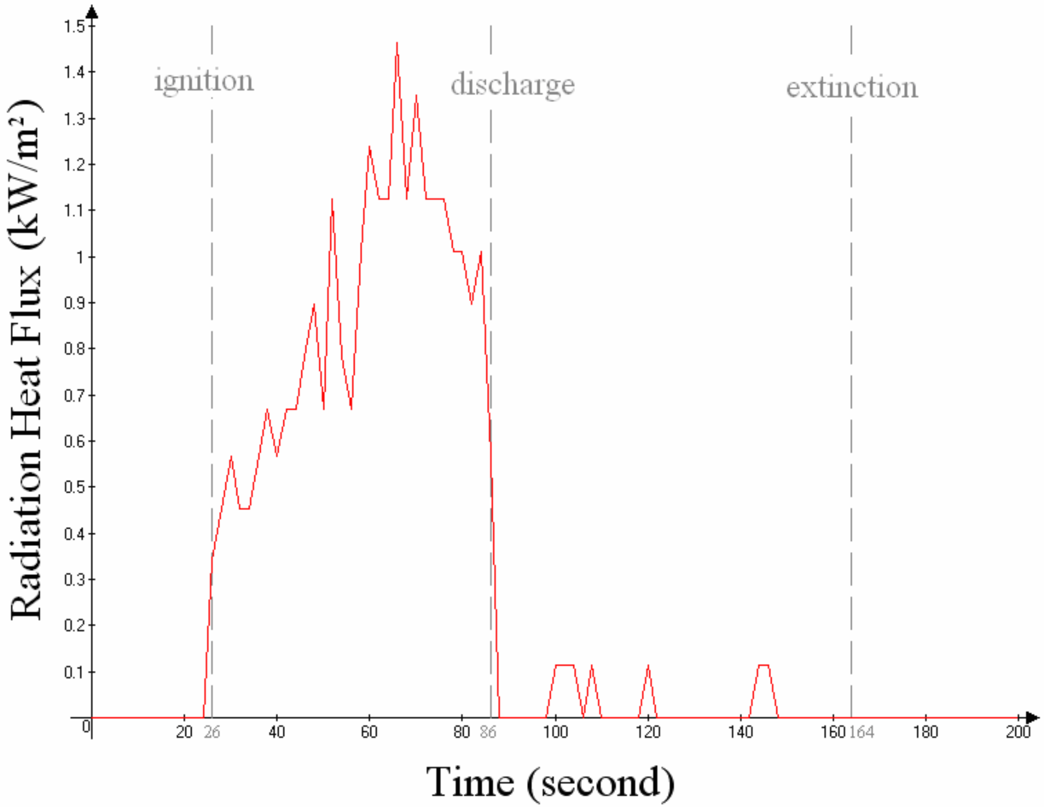
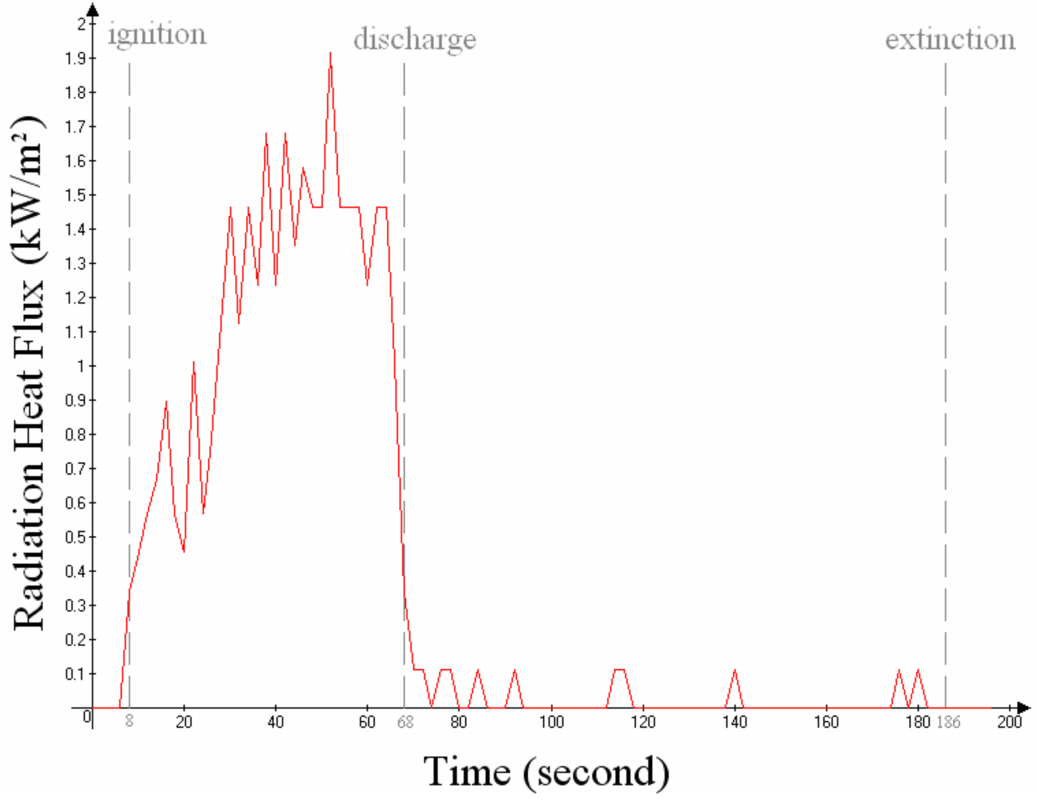


Fig. 4.2 The temperature history of fires with pure water at the nozzle discharge angle of 30° (a) Heptane (b) Gasoline (c) Diesel (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

(a) Heptane



(b) Gasoline



(c) Diesel

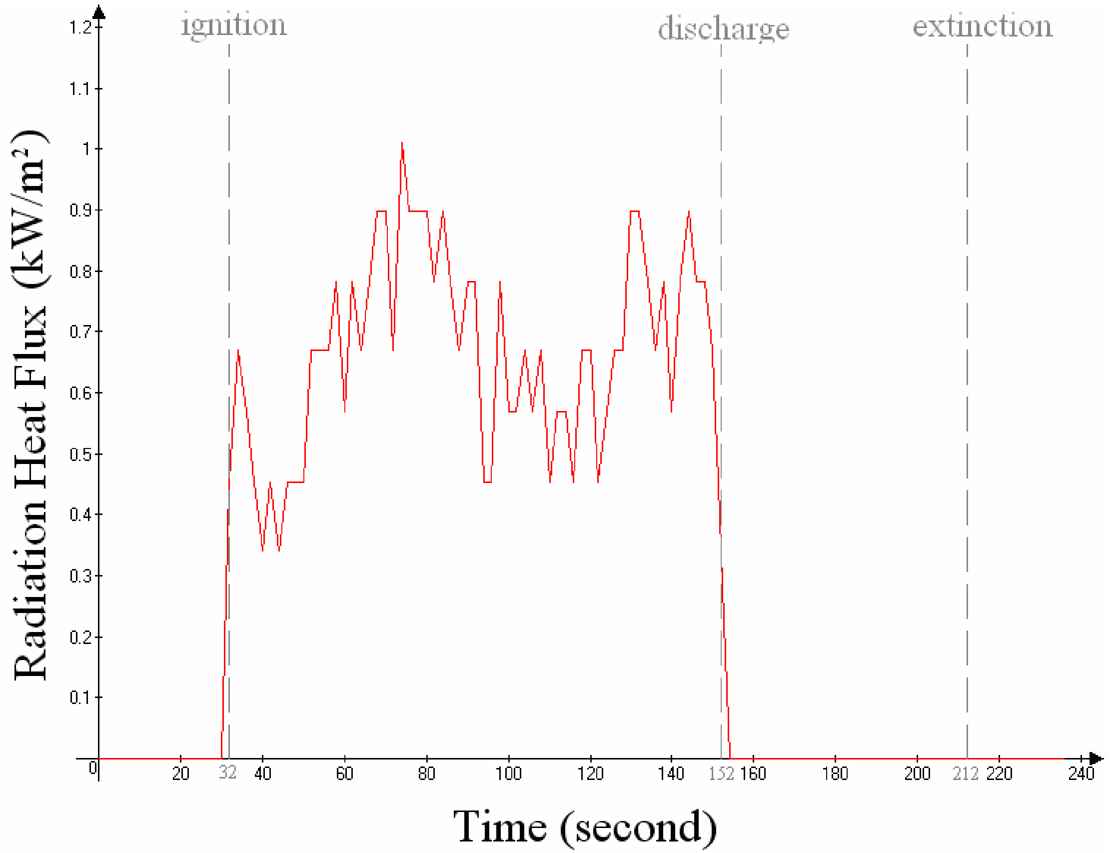


Fig. 4.3 The radiation heat flux history of fires with pure water at the nozzle discharge angle of 30° (a) Heptane (b) Gasoline (c) Diesel (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

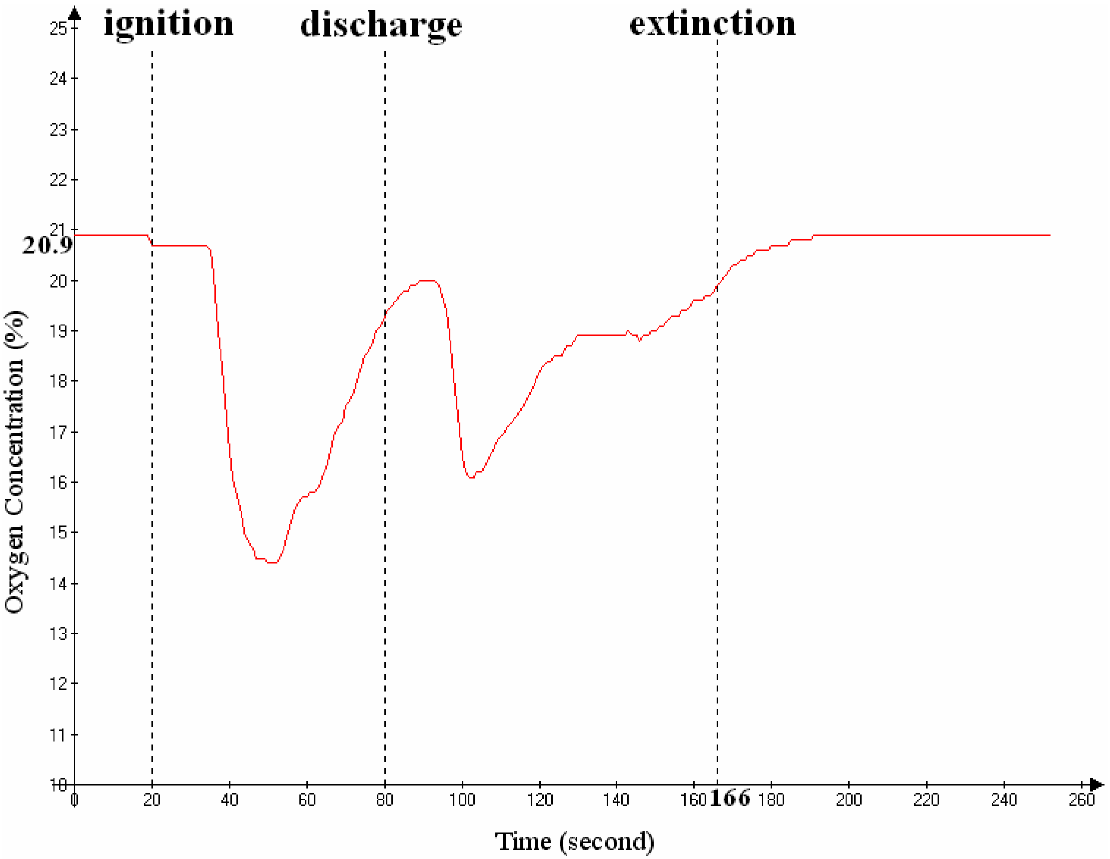


Fig. 4.4 Oxygen concentration variation history (Diameter of pan: 25*cm*, Fuel type: gasoline, Amount of fuel: 250*ml*, Nozzle discharge angle: 60°, Additive: 0%)

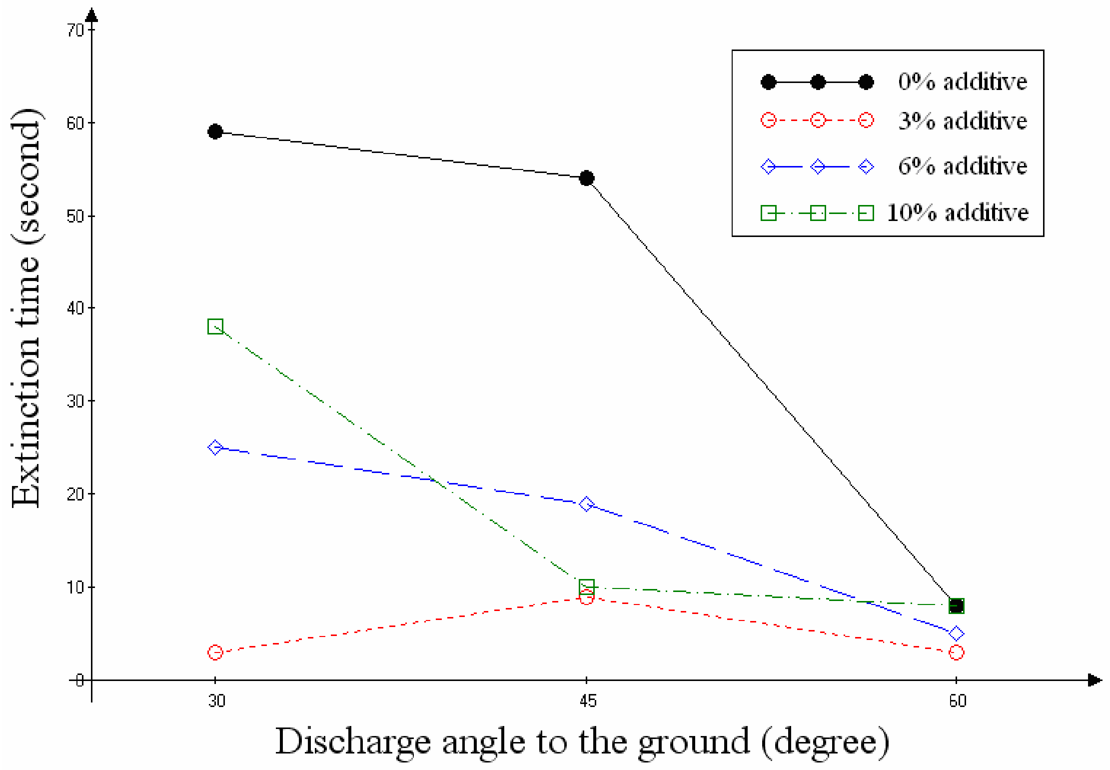


Fig. 4.5 Extinguishing time for diesel fire with different nozzle discharge angles and additive solution volumes (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

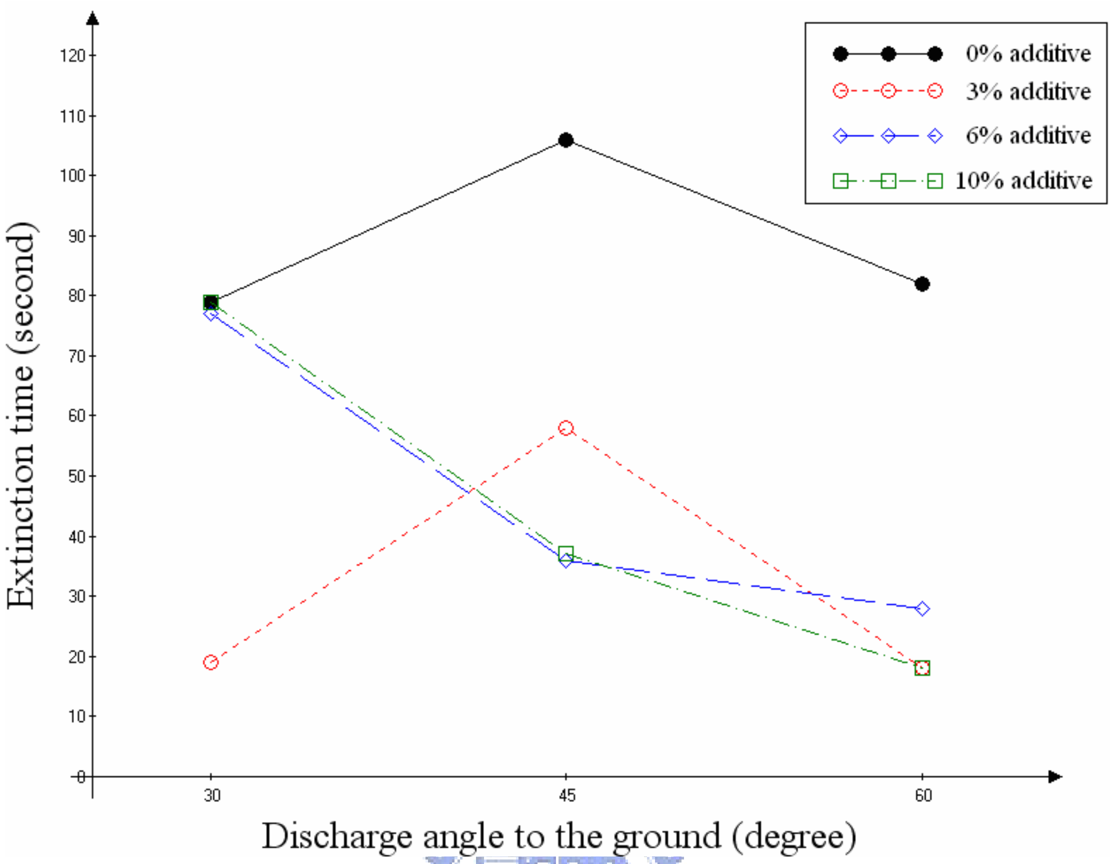


Fig. 4.6 Extinguishing time for heptanel fire with different nozzle discharge angles and additive solution volumes (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

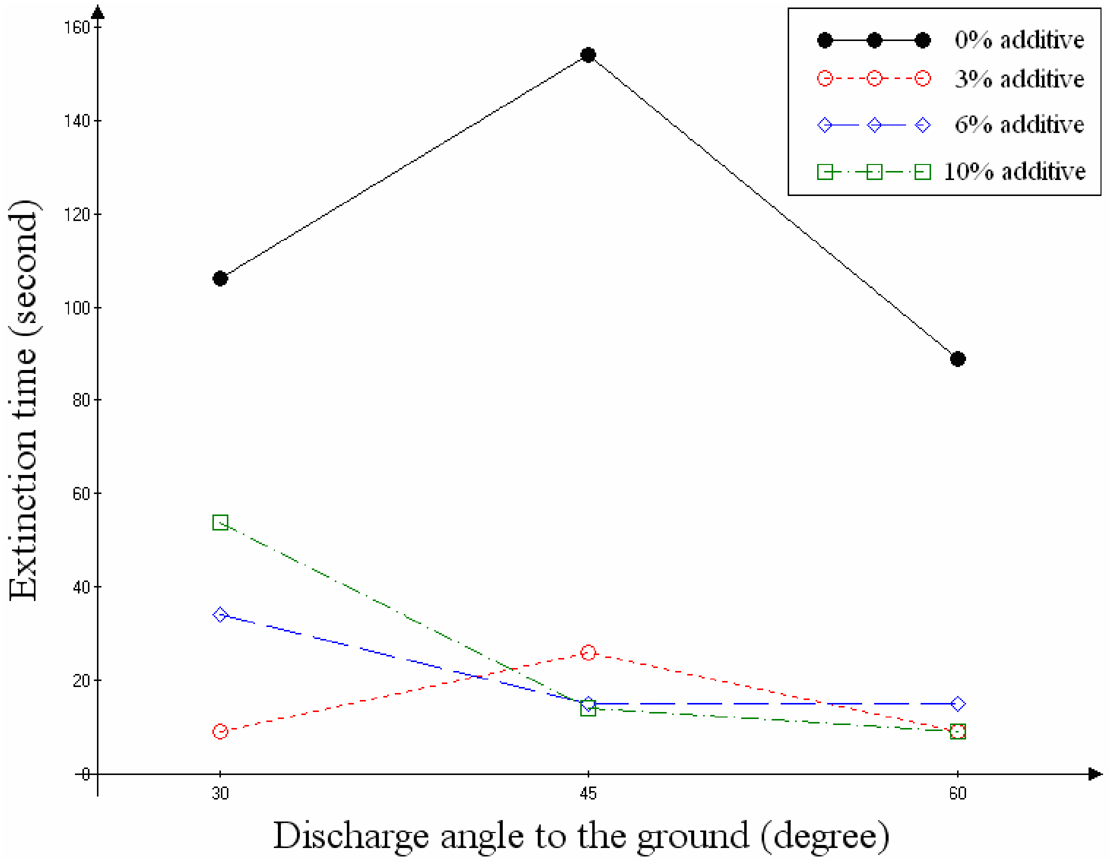


Fig. 4.7 Extinguishing time for gasoline fire with different nozzle discharge angles and additive solution volumes (Diameter of pan: 25*cm*, Amount of fuel: 250*ml*)

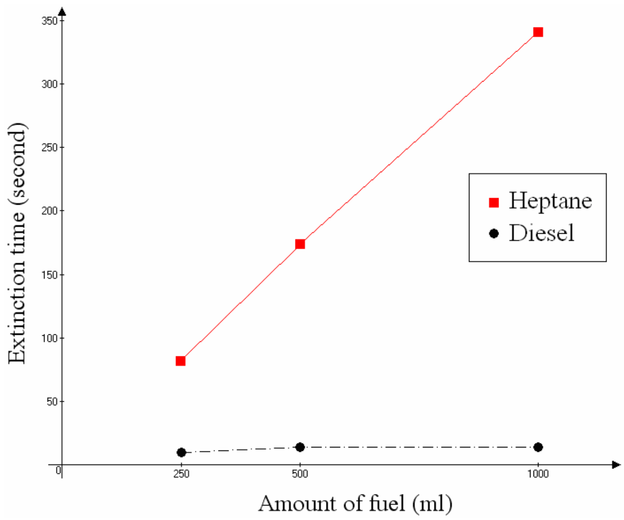


Fig. 4.8 The relationship between amount of liquid fuel and extinction time with 0% additive (Diameter of pan: 25*cm*, Nozzle discahrge angle: 60°)

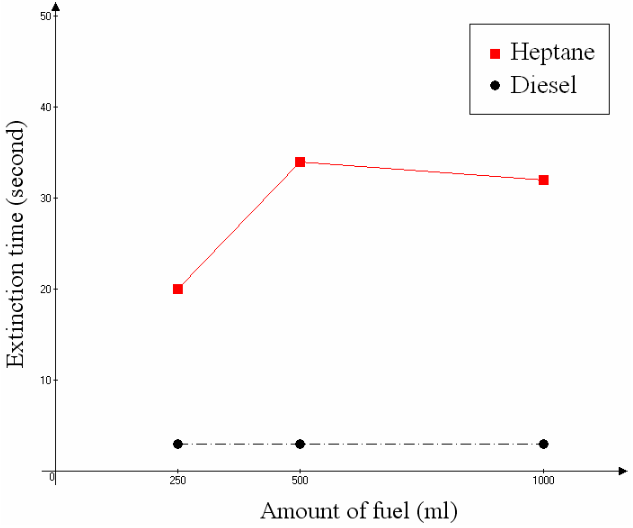


Fig. 4.9 The relationship between amount of liquid fuel and extinction time with 3% additive (Diameter of pan: 25*cm*, Nozzle discahrge angle: 60°)

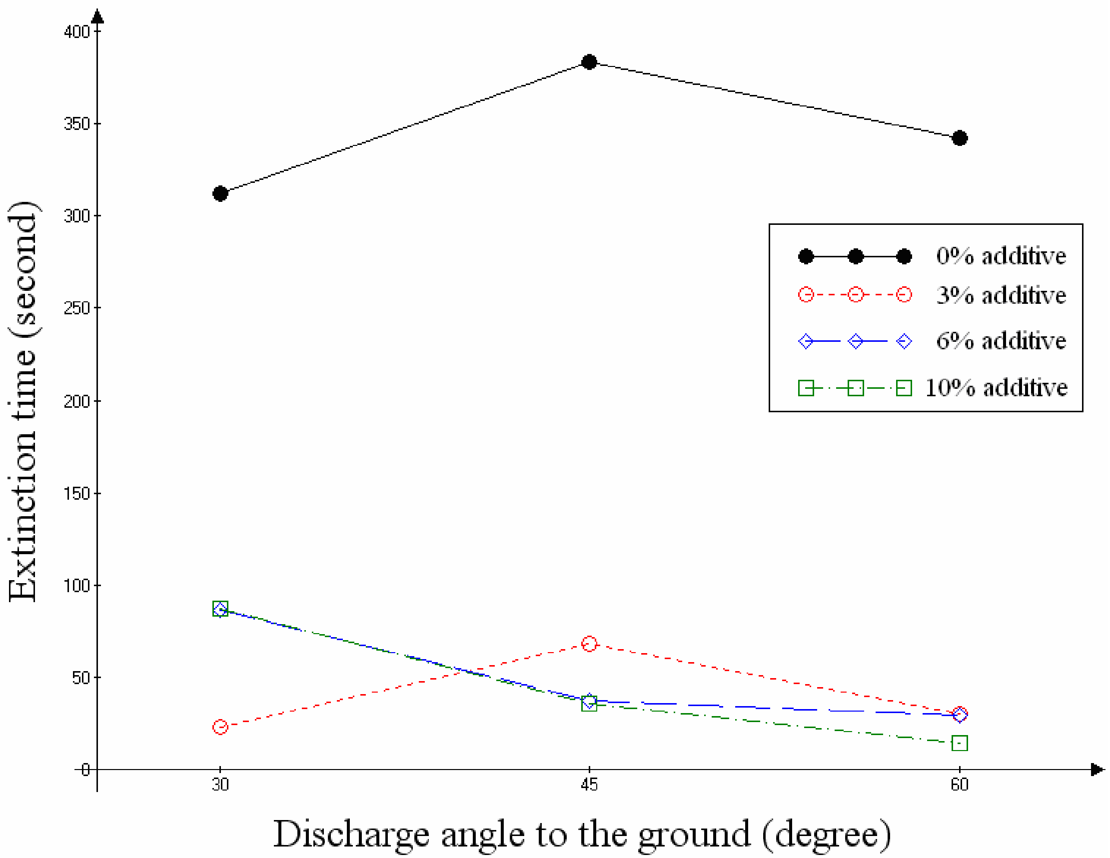


Fig. 4.10 Corresponding extinction time(sec) of Heptane fires with 2*cm* height of the liquid fuel (Diameter of pan: 25*cm*)

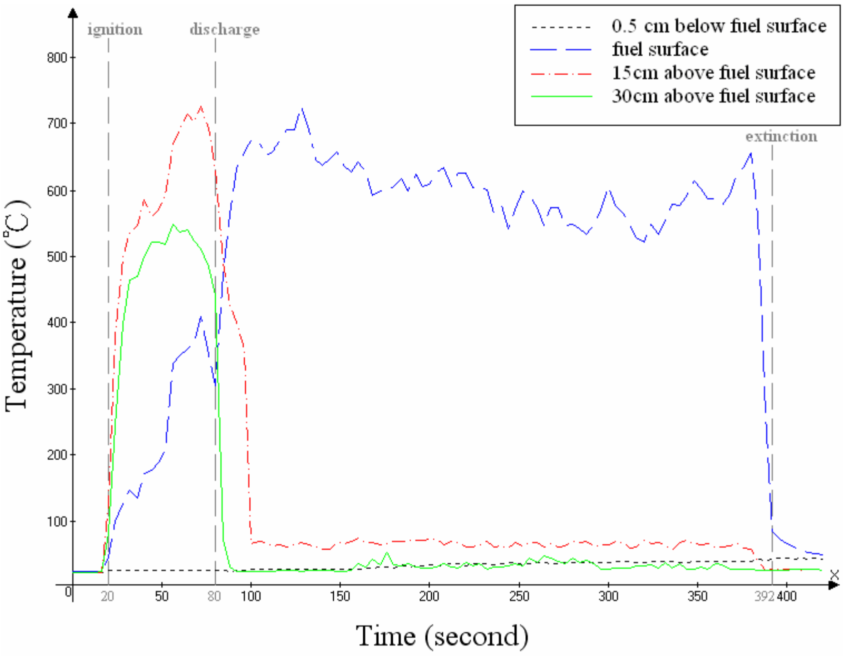


Fig. 4.11 The temperature history of of heptane fire (2*cm* height of liquid fuel) with pure water at the nozzle discharge angle of 30° and 25*cm* diameter of pan

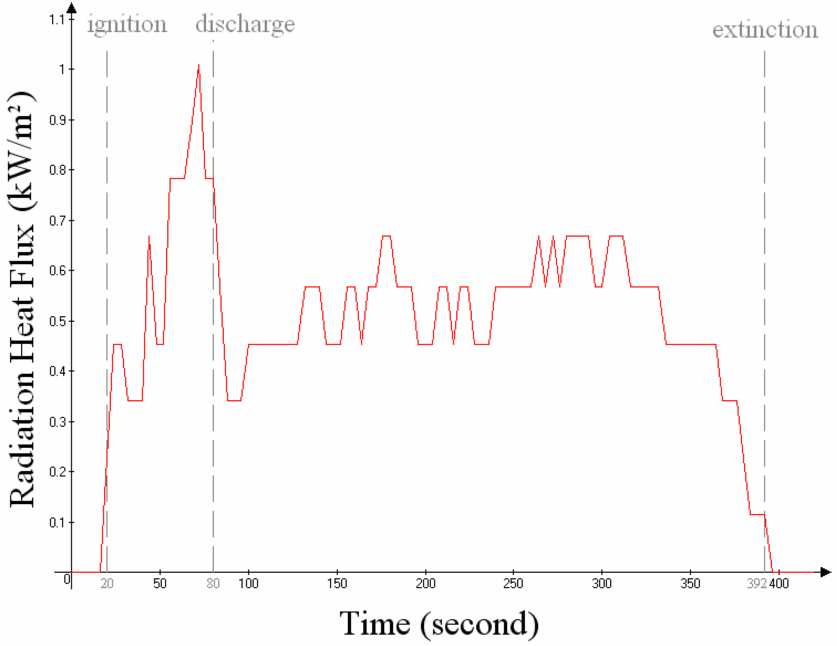


Fig. 4.12 The radiation heat flux history of heptane fire (2*cm* height of liquid fuel) with pure water at the nozzle discharge angle of 30°and 25*cm* diameter of pan

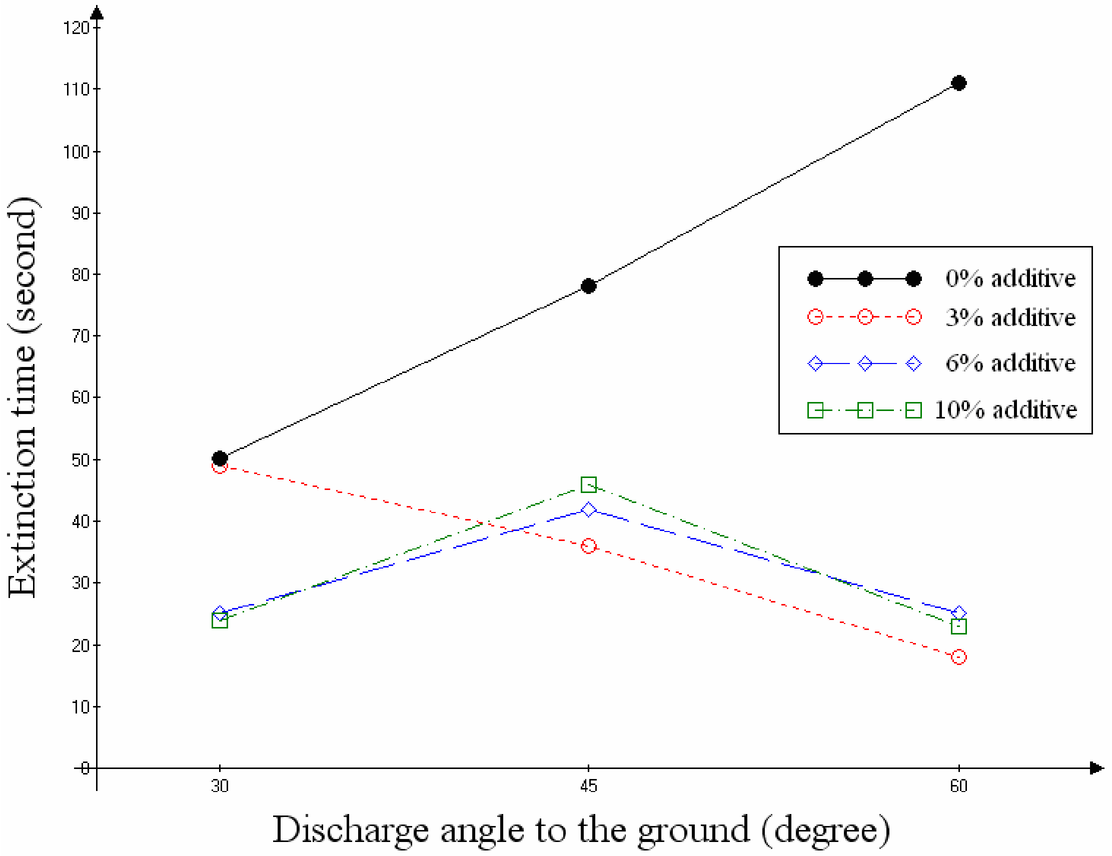


Fig. 4.13 Extinguishing time for heptanel fire with 50*cm* diameter of the pan (Height of liquid fuel: 0.5*cm*)

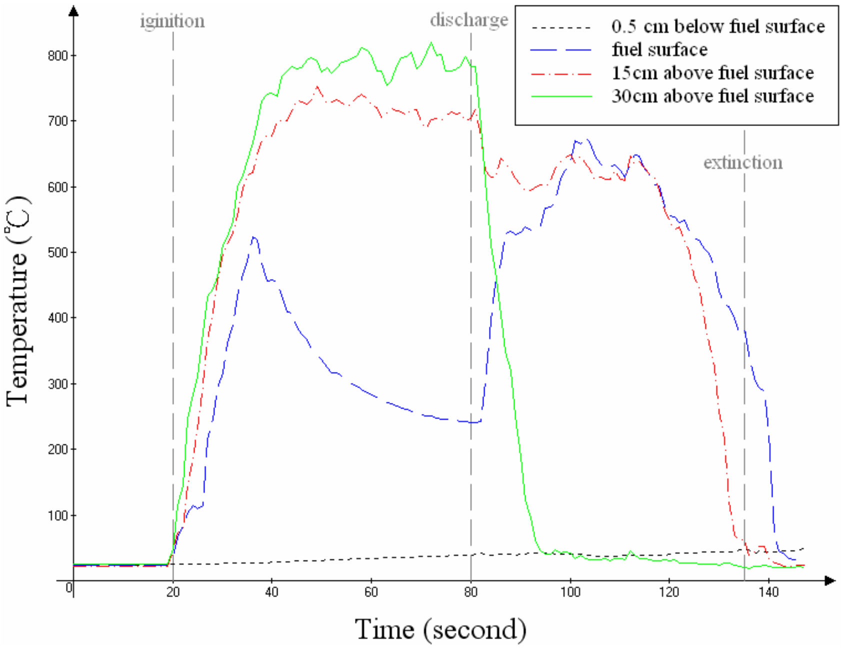


Fig. 4.14 The temperature history of heptane fire (50*cm* diameter of the pan) with pure water at the nozzle discharge angle of 30° and 0.5*cm* height of liquid fuel

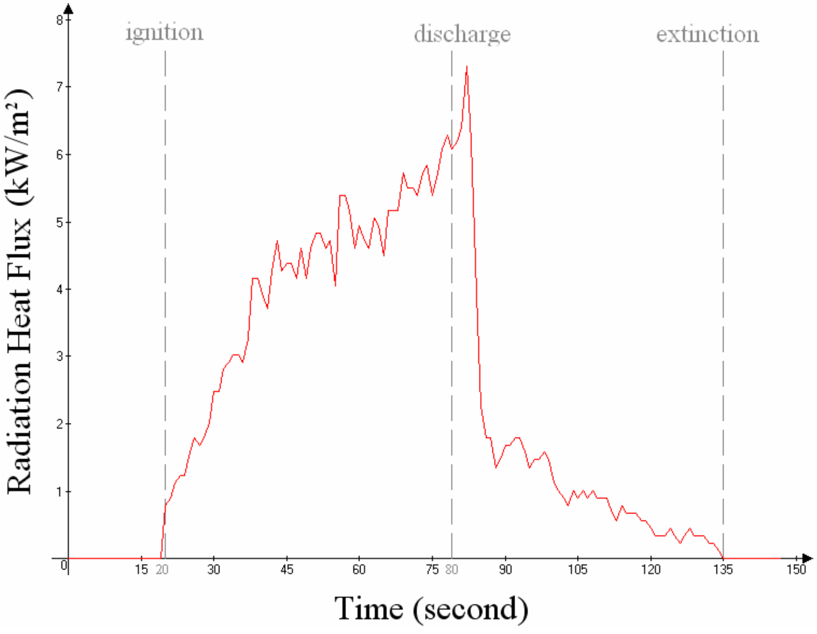


Fig. 4.15 The radiation heat flux history of heptane fire (50*cm* diameter of the pan) with pure water at the nozzle discharge angle of 30° and 0.5*cm* height of liquid fuel