CHAPTER 3

EXPERIMENTS

3.1 Introduction

As previously stated, the vapor explosion is caused by the process of fluid dynamics and by the rapid heat transfer process. During the event the major parameter driving the vapor explosion is the large difference in temperature between that of the molten fuel and the liquid coolant. In this experiment, the water at 300 K as the fuel simulant, while the liquid nitrogen at atmospheric pressure (-196 K approx.) as a coolant simulant are chosen and supposed to cause the vapor explosion.

Except the surrounding effect to the experimental system, the other parameters, which directly affect to the explosion, are the water properties, the liquid nitrogen properties, motion and geometry while the pressurization is the result of the interaction.

One in many parameters described above, the absolute viscosity, is directly related to the motion of the multiphase fluid. The viscosity contributes to the shear force especially between the water and liquid nitrogen interface in the BLS process.

The next parameter, which is related to the motion, is the velocity of the water. The velocity accompanying with the density of the liquid nitrogen, the water jet diameter, and the surface tension between the two liquids describes the momentum and the kinetic energy during the breakup process.

The geometrical parameters, such as the shape of the molten fuel and the configuration of the vessel structure, can be specified by the dimension in the form of the length, the area and the volume. The geometrical parameters are very important when one compares the different surface area for heat transfer between the spherical shape and the cylindrical shape of the same volume. Similarly, one may compare the shallow pool and the deep pool of the coolant with the same volume when the molten fuel comes into contact and penetrate through.

Some parameters, which have already been declared, may not be possible to observe in this experiment due to the limitation constraint in the resources and time available. However, two parameters can be controlled and measured such as water injection pressure and volumetric ratio of water to liquid nitrogen.

The injection pressure directly affects the velocity of the water in the liquid nitrogen. As the velocity increases, the fragmentation rate of the water in the liquid nitrogen increases, too. The larger surface area caused by the fragmentation also increases the heat transfer rate in many volumetric regions of the liquid nitrogen pool. The difference in the temperature between the water temperature and the liquid nitrogen temperature causes the boiling. The bubbles grow and coalesce to form the film. The instabilities causing the film to collapse and the liquid nitrogen jet impinging into the water are presumed to occur and finally result in the vapor explosion with the transient increasing in pressure, which can be observed.

For the volumetric ratio of water to liquid nitrogen in this experiment, the volume of water is measured directly by a beaker but the liquid nitrogen volume is indirectly measured by observing the formation of the ice on the outer surface of the container. If the volume of the liquid nitrogen was too low, the liquid nitrogen may be vaporized without the occurrence of the collapsing of the vapor film. As a result, the pressurization rate will also be low. By this reason, it is expected that there must be the volumetric ratio that defines the criteria at which the film collapse may occur and result in the vapor explosion. Hence, the pressurization is observed.

The result from the vapor explosion is the rapid pressurization. In this dissertation, this was measured by the maximum pressurization rate $\left(\frac{dp}{dt}\right)_{max}$ at the steep front of the pressure spike. It is one of the important keys to justify how severe the pressure force acts on the vessel or the containment.

The pressurization is measured with the piezo-resistive pressure sensor, which detects the pressure up to the frequency response of 5 kHz with the uncertainty less than 1%.

With the injection of the water into the liquid nitrogen pool, the interaction between both liquids is presumed to result in the explosion-like pressurization, which can be detected and analyzed. An analog to digital (ADC) card digitizes the analog signal from the pressure transducer with 14-bit resolution and less than 42 microseconds conversion time. The digital data is saved in a memory of a PC computer with time.

The time is detected from the counter timer chip (CTC). The chip is the main timing source on the PC computer. The resolution of the time is 0.8381 microseconds. The overhead for a count value from the chip is less than 23 counts or 20 microseconds. With the conversion time, the minimum sampling rate is 16 kilo samplings per second. Two signals from 2 pressure transducers and two counter times need 64,000 data in one second. Presuming that the explosion-like signal occurs within 6 seconds, a large memory block is necessary. The 32-bit addressing C language is required. The detail of the timer and the management of the large memory block for sampling data are shown in appendix A.

The ice debris is used to investigate the violence of the interaction. The camera is needed to capture the debris, and the photographs are analyzed. Furthermore, the necessary data from the experiment will be tested with the available computer code developed for the high-temperature vapor explosion in order to test the results of vapor explosion at the low temperature.

3.2 Physical and thermodynamic properties

The experiments have been conducted in cryogenic temperature range. Some physical and thermodynamic properties of water and liquid nitrogen have been collected and listed in table 3.1. Generally, the physical and thermodynamic properties of both liquids are changing during the interaction. However, the properties can be approximated to those at the atmospheric pressure.

Table 3.1 Some physical and thermodynamic properties of water and liquid nitrogen [5,6]

Property lists	Water	Liquid nitrogen
Initial temperature	300 K	77 K
Density	997 kg/m^3	806 kg/m^3
Viscosity	$8.5x10^{-4}$kg/m-s	$1.57x10^{-4}$kg/m-s
Surface tension	$72x10^{-3}$N/m	$6.2x10^{-3}$ N/m
Thermal conductivity	0.614 W/m-K	0.139 W/m-K
Specific heat	4179 J/kg-K	2040.8 J/kg-K
Latent heat	333 kJ/kg for fusion	199.3 kJ/kg for vaporization
Critical temperature	647.29 K	126.192 K
Critical pressure	22.09 MPa	3.3958 MPa

3.3 Explosion Chamber Design

In the experiment, the interaction is supposed to occur. And its consequence is the pressurization in the close volume or "chamber". The predicted final pressure must be known in order to design the chamber rating. Before predicting the final pressure, the final temperature of the well mixing between the 400 g water at 300 K and the 1600 g (~2000 cc) liquid nitrogen at 77K, constant atmospheric pressure, is estimated for the isobaric process by equation (3.1).

$$m_w c_w (T_w - T_{melting}) + m_w L_w + m_w c_{ice}(T_{ice} - T_{final}) = m_{n2} L_{n2} + m_{n2} c_{n2}(T_{final} - T_{saturation}) \quad (3.1)$$

where m is the mass, c is the specific heat, L is the latent heat, T is the temperature, the subscript w is for the water, and the subscript $n2$ is for the nitrogen.

The calculated temperature is ~90K at atmospheric pressure and 0.4 cubic meter. In this state, all liquid nitrogen is presumed vaporized. The geometry of the chamber is designed for studying process in one-dimensional fashion. The chamber has the diameter of 0.1 meter and its height is 1 meter. The volume of the chamber is 0.008 cubic meter, 1/50 times of the calculated volume, 0.4 cubic meter. Based on this configuation, the predicted pressure produced in the chamber is 50 bar.

In general, the conversion efficiencies in many of the past reference experiments are from 0.1 to 10%. Then, the maximum produced pressure during the interaction is estimated at 5 bar. Fortunately, a pipe with 4-inch diameter and schedule number #40 is available. Its thickness is 6 mm. And its strength is 120 bar at exceptionally low temperature according to the "JIS HANDBOOK on Piping [35]". Such pipe provides a safety margin for the experiment.

The maximum pressure was also calculated by using EES [36] under the same chamber geometry but with 100g water and 1000g liquid nitrogen at 1-bar initial pressure [12]. The final pressure was predicted to be 14 bar. This prediction is also under the margin provided by the chosen materials.

3.4 Finished installation

The finished installation for the low temperature vapor explosion is divided into 4 parts. The first part is the explosion chamber in which the interaction between the water and the liquid nitrogen interaction occurs. The second part is the water injection system that injects the water into the explosion chamber. The third part is the liquid nitrogen loading system. The last part is the automatic controller system. The actual design of the whole installation and the designed explosion chamber are given in Fig. 3.1 and Fig. 3.2. The automatic controller relay and power diagram is shown in Fig. 3.3 and Fig. 3.4. The photographs of the finished installation and its various parts are also given in Fig. 3.5, 3.6, 3.7, and 3.8

3.5 Explosion Chamber

The explosion chamber connects to a liquid nitrogen inlet valve (CV1), a water inlet valve (CV2), a nitrogen gas discharge valve (DV1), a pressure relief valve (PV1), a solenoid valve (SV2), two electronic pressure transducers (PT1 and PT2) and a mechanical pressure gauge.

3.5.1 Liquid Nitrogen Inlet Valve

The liquid nitrogen inlet valve (CV1), also called the lift check valve, was designed to operate at the low temperature. According to the specification given by the manufacturer, the valve that is used for the experiments has the lowest operating temperature of –190C or 83K. It is made of the stainless steel with the pressure rating of 40,000 kPa by mean of the metal-to-metal seal.

3.5.2 Water Inlet Valve (CV2)

CV2 is used for the water injection system. It allows the water flow from the solenoid (SV1) while, at the same time, prevents the back flow from the explosion chamber due to the high pressure from the explosion inside the chamber. It can withstand the back pressure up to 2,000 kPa.

3.5.3 Nitrogen Gas Discharge Valve (DV1)

DV1 is to be opened in order to relief the pressure inside the chamber, during the liquid nitrogen loading and after the experiment is concluded. A ball valve is chosen for the installation.

3.5.4 Pressure Relief Valve (PV1)

The valve is also called the safety relief valve. Its principal parts (valve case and its seal) are made of the stainless steel. The adjustable ring allows the blow-down pressure to be varied from 500 to 1,600 kPa (gauge). For the experiment, this is set at 1,500 kPa (gauge).

3.5.5 Solenoid Valve (SV2)

SV2 is designed to relief the high pressure inside the chamber by discharging the vaporized nitrogen gas so that the experiment can be concluded. This valve can be operated in the range of 100 to 2,000 kPa (gauge).

3.5.6 Electronic Pressure Transducer (PT1)

PT1 is installed 31 centimeters from the bottom of the chamber. It measures the vapor pressure inside the chamber. Its sensor is made of piezo-resistive. The operating temperature range is from –40 C to +125 C with thermal sensitivity shift ≤ ±0.015%FS/°C, according to the manufacturer specification. During the liquid nitrogen loading, a portable digital thermometer measures the wall temperature outside the chamber 24 centimeters above the bottom. And it shows –40 C.

3.5.7 Electronic Pressure Transducer (PT2)

PT2 is the same model as PT1. It is installed at the top of the chamber.

3.5.8 Mechanical Pressure Gauge (PG1)

The mechanical pressure gauge can measure the pressure in the range 0-2,500 kPa (gauge). Its accuracy is ±1.6% of its full range with the normal operating temperature of 20 C or 293 K. The pin pointer on this gauge can show the bouncing during the interaction and the warning index when the high pressure is relieved.

3.6 Water Injection System

The water injection system contains an air compressor, a coupling valve, a water bottle (WB1), and a solenoid valve (SV1).

3.6.1 Air Compressor (AP1)

The air compressor is used to pressurize the water bottle to the desired pressure level of 300 kPa (gauge).

3.6.2 Coupling Valve

Its function is to simply connect the air compressor to the water bottle.

3.6.3 Water bottle (WB1)

The bottle can contain up to 500 cc of water and can withstand the pressure up to 400 kPa.

3.6.4 Solenoid Valve (SV1)

SV1 is normally closed so that the water can kept under the desired pressure in the water bottle. It is open only to inject the water into the chamber through the check valve (CV2).

3.6.5 Mechanical Pressure Gauge (PG2)

This pressure gauge measures the desired pressure inside the water bottle. And its accuracy is ±1.6%.

3.7 Liquid Nitrogen Loading System

The liquid nitrogen loading system contains an air pump (AP2), the rubber tube, the liquid nitrogen dispenser and the liquid nitrogen tank.

3.7.1 Air Pump (AP2)

This pump gently pushes the air into the liquid nitrogen tank through the liquid nitrogen dispenser. The air will then drive the liquid nitrogen from the tank to the explosion chamber.

3.7.2 Rubber Tube

This rubber tube provides the route for the liquid nitrogen to flow from the tank through the dispenser to the explosion chamber via the lift check valve (CV1).

3.7.3 Liquid Nitrogen Dispenser

The dispenser is the interface between the air and the liquid nitrogen. It has two tubes. One is a short tube that is used for the air inlet flow. The other one is a long tube that is used for the liquid nitrogen outlet flow. These tubes are made of the stainless steel.

3.7.4 Liquid Nitrogen Tank

The tank is specially made for keeping the liquid nitrogen. It can contain up to 20-kg of the liquid nitrogen.

3.8 Procedure for Conducting the Experiment

In this section, the recommended procedure for conducting the experiment is given. It is suggested that the procedure should be followed in the given order. This is to prevent the mistake that may endanger to life and render the experiment useless or inefficient.

3.8.1 Water Loading

1. Ensure that the handle of the discharge valve (DV1) opens and solenoid valve (SV1) is turn off.
2. Load the desired amount of water into the water bottle.
3. Connect the air compressor to the water bottle via the coupling valve.
4. Turn on the compressor. Turn off the compressor when the desired pressure level is reached.

3.8.2 Liquid Nitrogen Loading

1. Connect CV1 to the bottom of the explosion chamber.
2. Connect the outlet for the liquid nitrogen from the liquid nitrogen dispenser and CV1 with the rubber tube.
3. Install the liquid nitrogen dispenser to the liquid nitrogen tank.
4. Connect the air inlet of the liquid dispenser to the air pump (AP2).
5. Turn on the controller breaker (CB1) shown in Fig. 3.3. Its function is to control all the procedure after the completion of liquid nitrogen loading.
6. Turn on AP2 at the front of the controller panel.
7. As a way to estimate the height of the loaded liquid nitrogen in the explosion chamber, observe the formation of the ice layer on the outer wall of the chamber.
8. Close DV1 when the height of the ice layer reaches the desired level.

3.8.3 Water Injection, Initiating the explosion

1. Once DV1 close, its handle pushes a limiting switch. The controller stops AP2 upon the signal from the switch. Then the controller opens the SV1 for water injection and sends a 5-volt signal to ADC card to set time zero for recording by computer.
2. Observe the mechanical pressure gauge if pressure spikes occurs.
3. After the interaction, the pressure continues to rise. The pressure relief valve, which is set to start relieving the pressure when reaching 5 bar, is activated. The pressure starts relieving and a sound can be heard very clearly. The pressure in the chamber still rises.

3.8.4 Post Experiment

1. Observe the pressure gauge of the chamber whether the pressure falling back to 7 bar and the relief sound is quiet.
2. If the sound disappears and the pressure gauge comes back to 7 bar, push button to turn on SV2 at the front of the controller panel. Caution! The discharge noise can be very loud. Before SV2 turn on, the controller closes SV1 automatically.
3. Disconnect the cover and the water injection system at the top of the explosion chamber.
4. Check the water in WB1 to ensure that the water is all injected. If it is not, the actual amount of water injected must be corrected. If possible, observe the formation of the fine particles of ice as a result of the interaction at the bottom and the inner wall of the chamber.
5. Wait until the ice formed at the bottom of the chamber and around CV1 is all melt. Then, disconnect CV1 from the chamber in order to drain the water out of the chamber. It is recommended that the amount of the drained water be checked whether it agrees with the amount of the water that is expected for the injection.
6. Disassemble the lift check valve (CV1). Dry the valve for ready to use next experiment. Caution! a little amount of water inside this valve will form ice and obstruct the valve-close completion in the next experiment and cause the explosion pressure leak back to the liquid nitrogen tank.

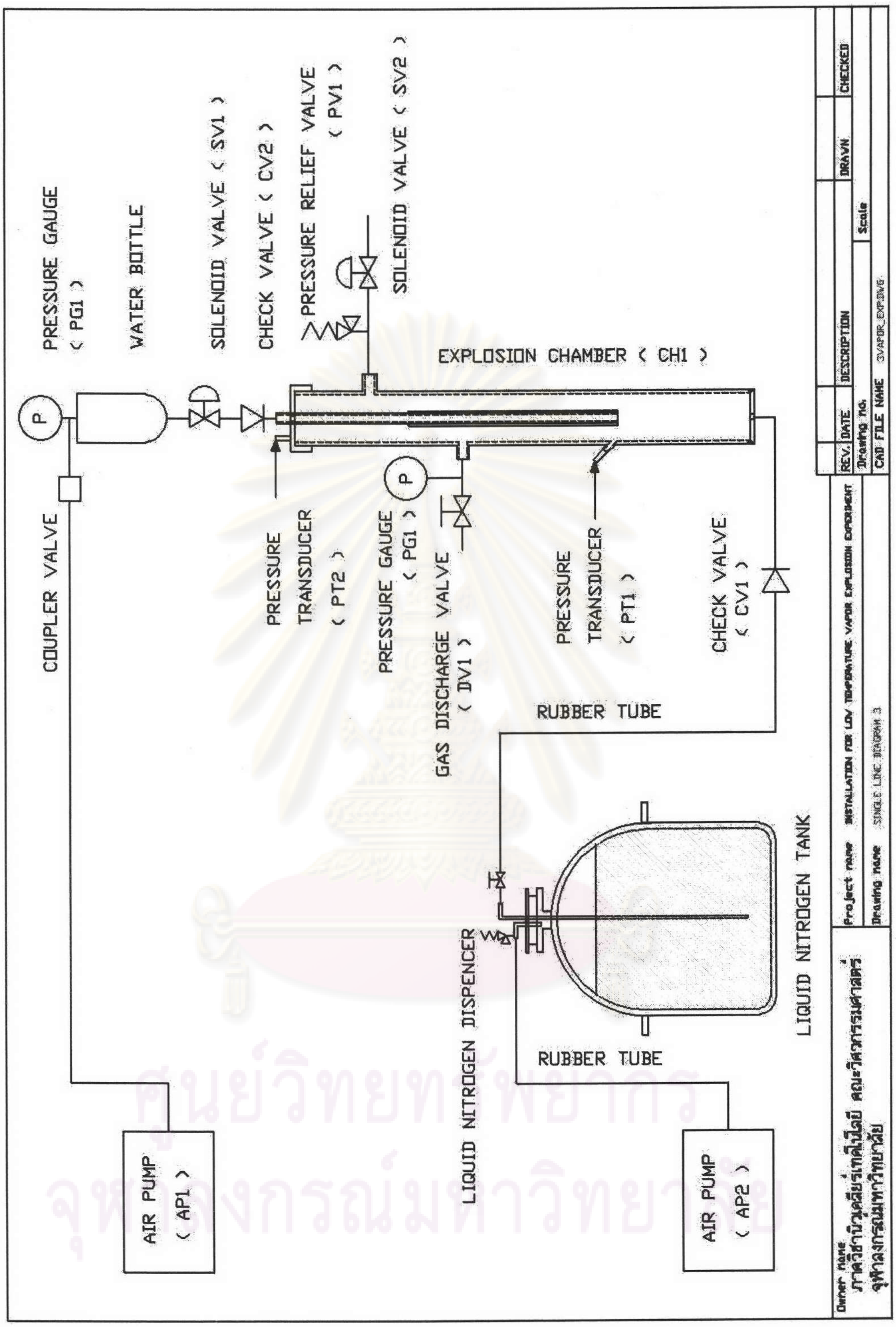

Fig. 3.1 Drawing of the actual installation for the low temperature vapor explosion

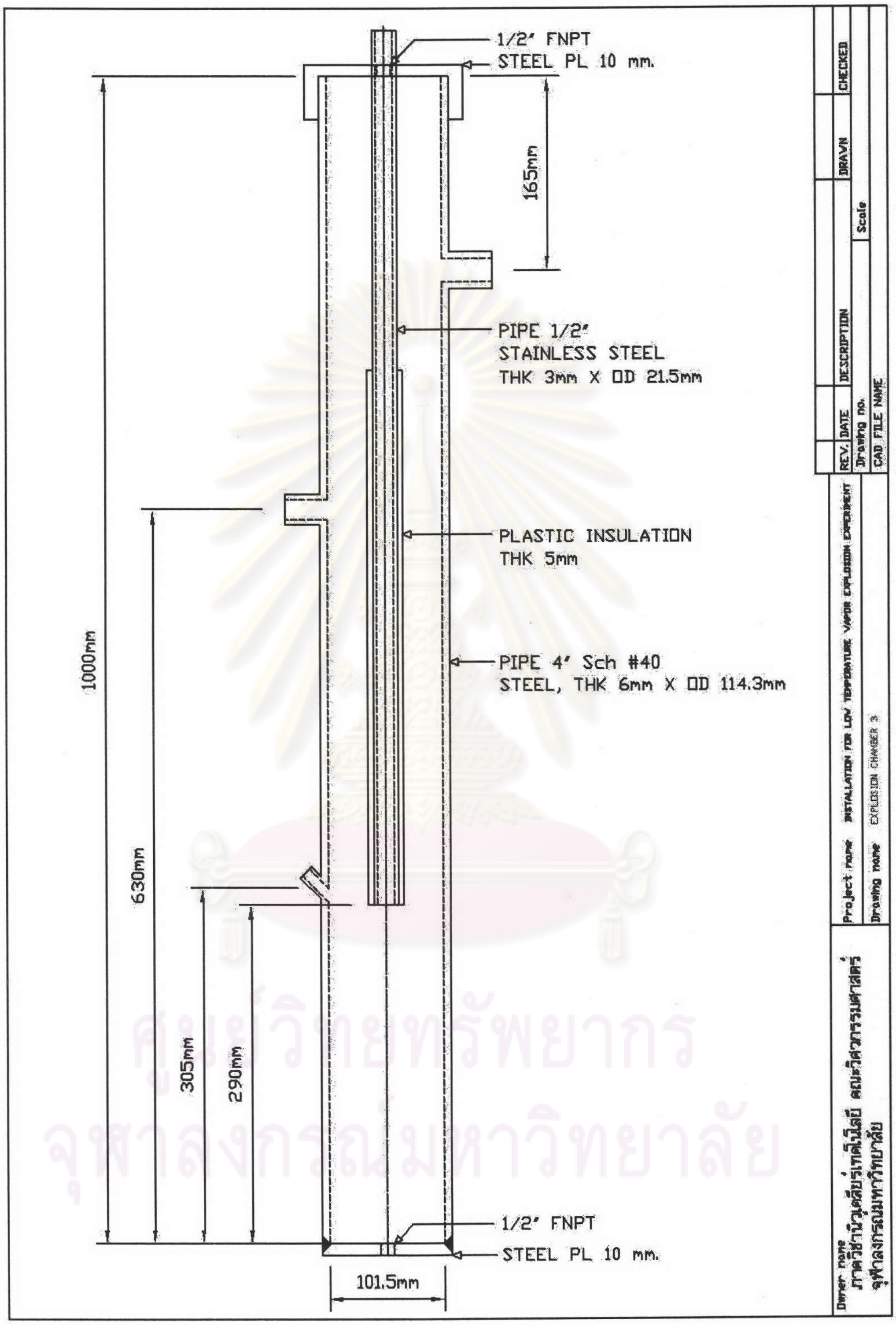

Fig. 3.2 Drawing of explosion chamber

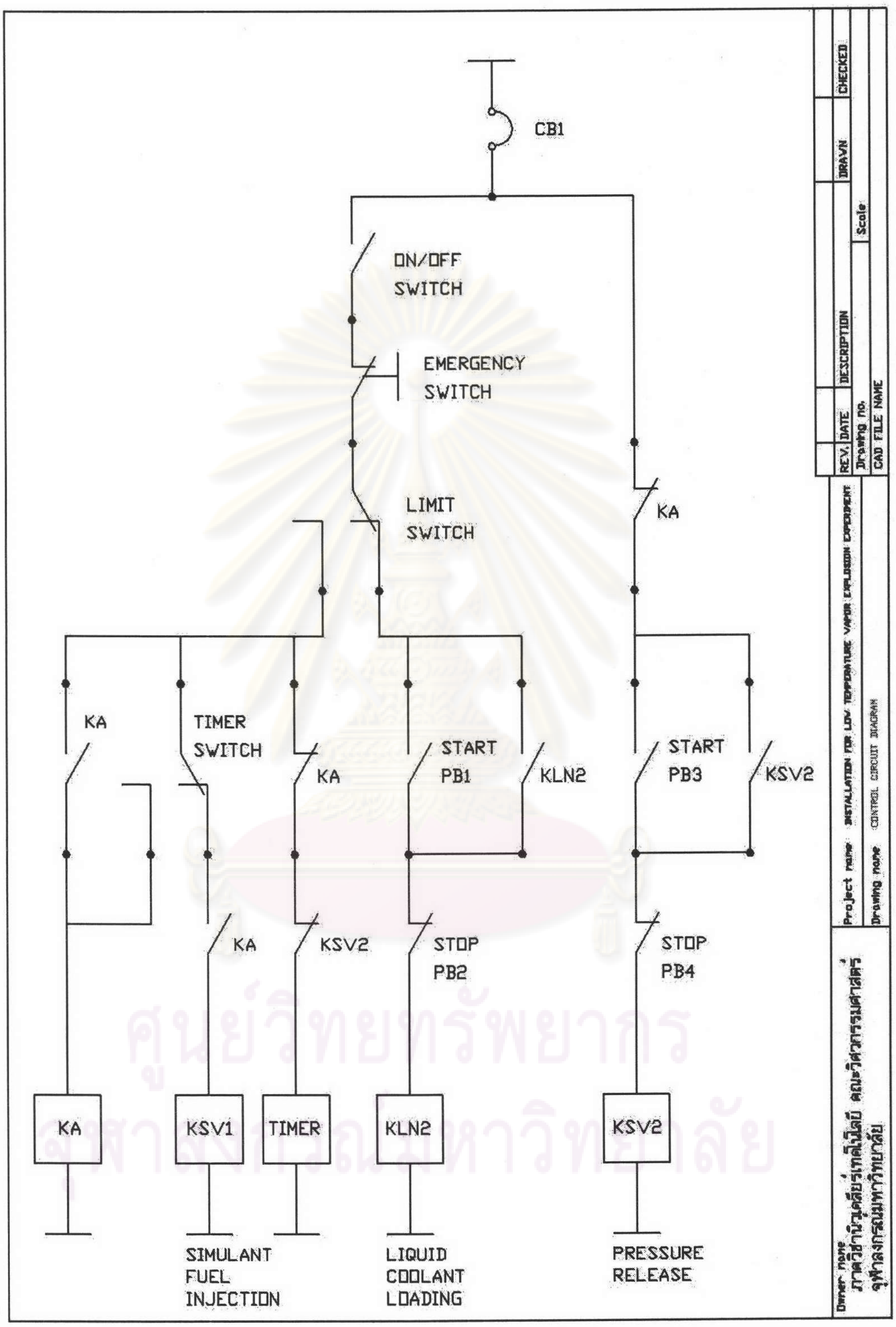

Fig. 3.3 Schematic diagram of the controller

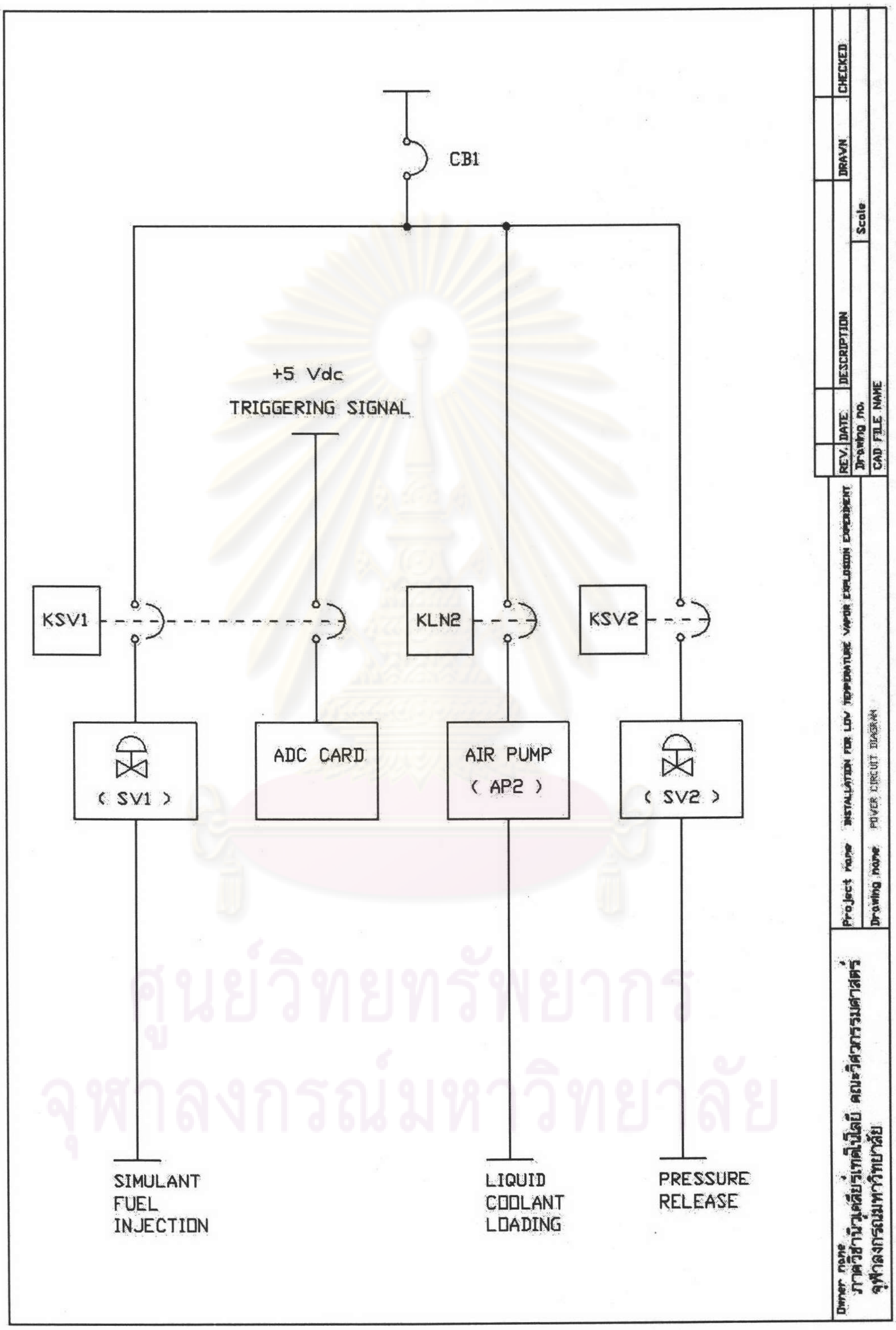

Fig. 3.4 Schematic diagram of the power diagram

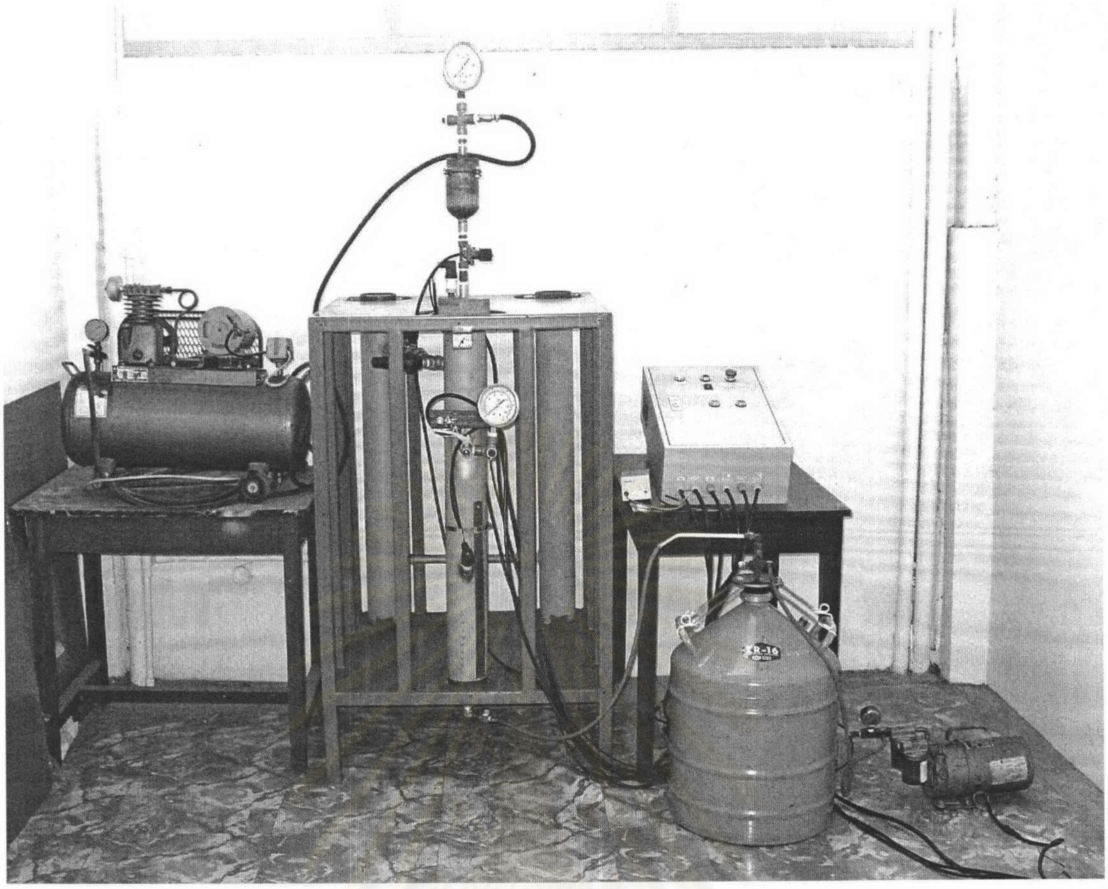

Fig. 3.5 Finished installation

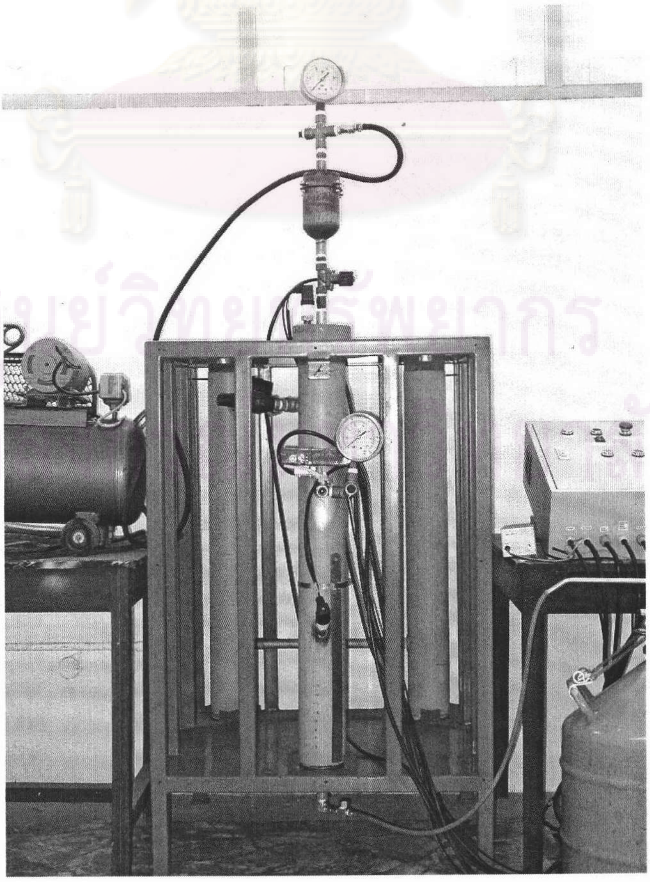

Fig. 3.6 Explosion Chamber

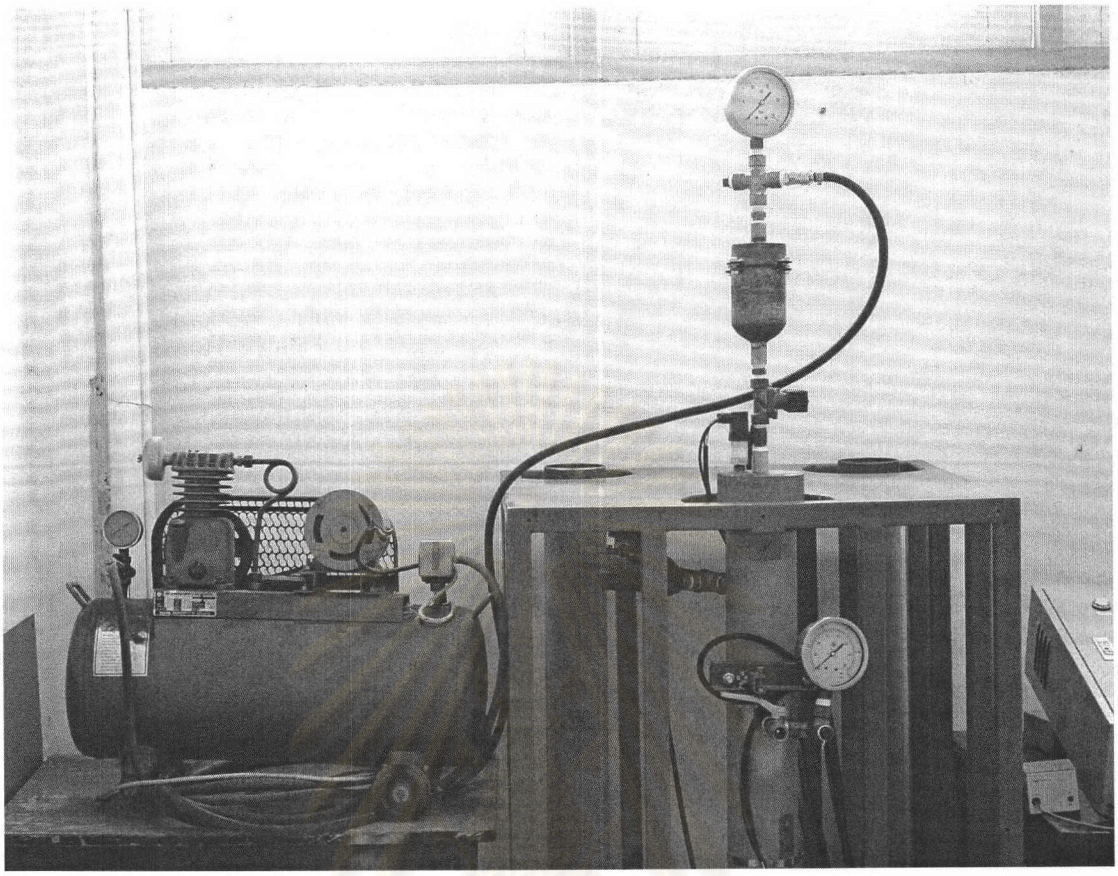

Fig. 3.7 Water injection system

Fig. 3.8 Liquid nitrogen loading system