CHAPTER III

The Experimental Refrigerator

An experimental refrigerator was designed to test a diffusion absorption refrigeration cycle. The capacity of each component was designed based on data listed in table 3.1. They were used as a guideline. It was expected that the actual operating conditions would be different from the calculated values. Therefore, all the components were over-sized. Figure 3.1 and 3.2 shows a photograph and a schematic diagram of the entire system respectively.

Table 3.1 Design data for the experimental refrigerator

generator temperature (°C)	150-200
rectifier exit temperature (°C)	50-90
absorber temperature (°C)	30-50
condenser temperature (°C)	30-50
generator heat input (W)	3000
cooling capacity (W)	600

3.1 Construction material

All the material used must be able to withstand pure ammonia and its aqueous solution. The major disadvantages of ammonia are its high condensing pressure, toxicity and corrosive to copper and copper alloy. The system maximum pressure and temperature were 20 bar and 200°C respectively.

All vessels were constructed from stainless steel 304 schedule 10s pipes. Fittings, valves, and tubes used were made from 316 stainless steel. Sealing materials (o-ring) were EPDM for temperature below 150°C and PTFE for temperature above 150°C. Liquid Teflon was used as thread sealant for all thread fittings.

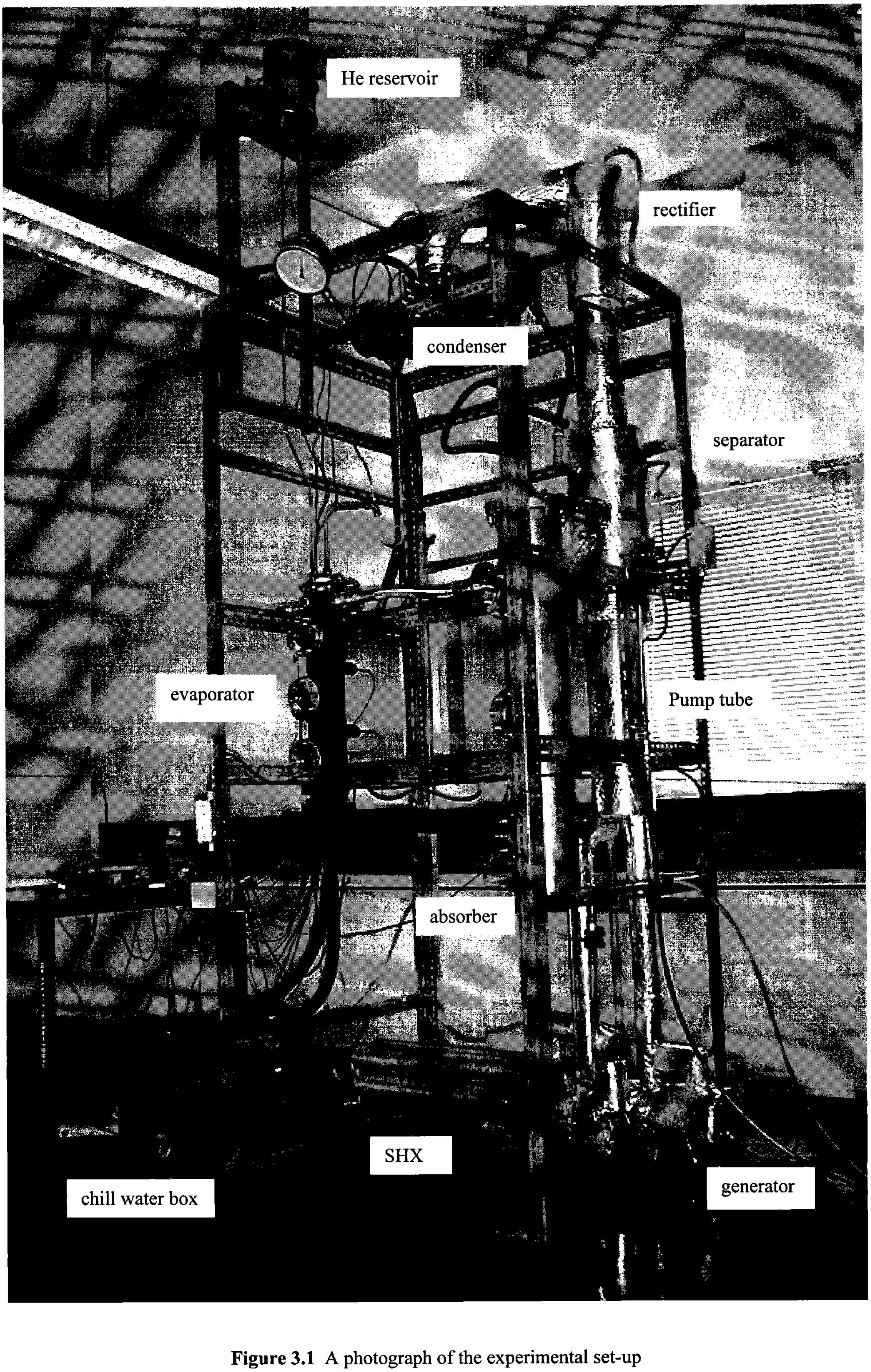

Figure 3.1 A photograph of the experimental set-up

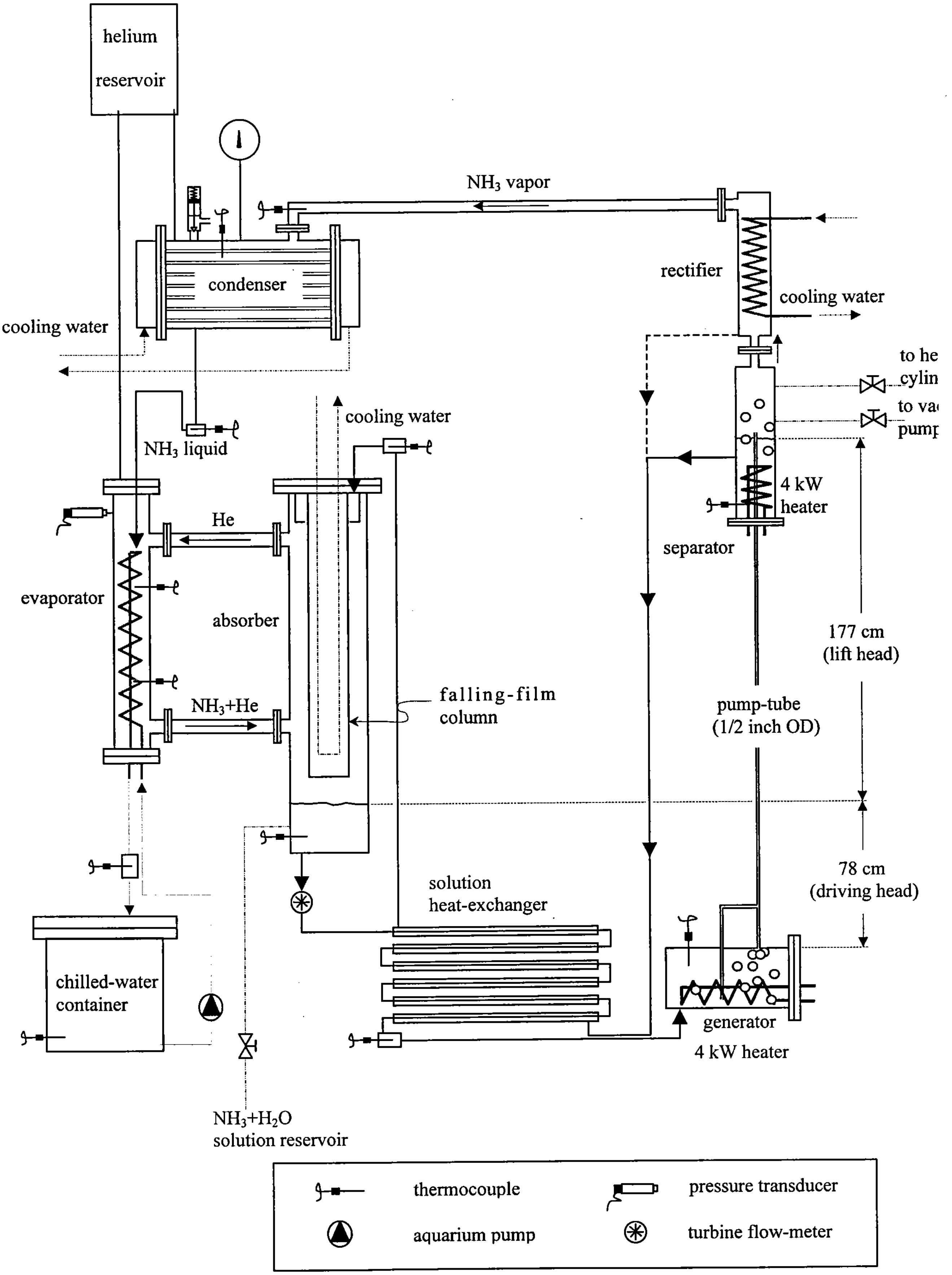

Figure 3.2 Schematic view of the experimental refrigerator.

3.2 The condenser

The condenser was designed based on a shell and tubes heat exchanger, cooling water was arranged to flow through the tubes. It was designed for 8 kW of heat load. It consisted of sixty 10 mm OD tubes, which provided total surface area of 1.2 m^2. The shell was constructed from a 0.50 m long 6-inch pipe. The condenser was equipped with a sight glass. The sight glass was 12 mm thick tempered-glass with 80 mm diameter.

3.3 The solution heat exchanger (SHX)

The solution heat exchanger consisted of six double pipe heat exchangers connected in series. The hot solution from the separator and the warm solution from the absorber flowed counter currently through the annular duct and inner tube respectively. The inner tube was a 12 mm OD seamless tube while the outer was a half-inch pipe. The total length was 6 m, which provided a total heat transfer area of 0.25m^2.

3.4 The evaporator

In the evaporator of conventional refrigeration systems, when pressure is abruptly dropped, liquid refrigerant evaporates to vapor at low temperature as it absorbs heat from a cooling space. The refrigerant is evaporated as it is heated in the same way as water in a kettle. The evaporation rate is controlled by an amount of heat input.

In an evaporator of a diffusion absorption system, liquid ammonia evaporates in an environment of an auxiliary gas (hydrogen or helium). This process is similar to how water evaporates from a wetted cloth. The evaporation rate is increased if the cloth is exposed to blown air or its evaporation rate can be enhanced more with reduced humidity of the air. Thus, the evaporator must be designed with enough wetted surface area. The pressure dropped must be minimized, in order to allow the inert gas to circulate.

The constructed evaporator consisted of a vertical coiled tube installed inside a shell pipe. Liquid ammonia was allowed to drop on the top to create a liquid film and evaporate in an environment of helium on the outer surface of the coil. The cooling load was obtained as circulation of chilled water through the coil.

The coil has a pitch diameter of 55 mm and 0.6 m long. It was made from 6 m of 10 mm OD seamless tube. This provided a total area of 0.19 m^2. The shell was constructed from a 3-inch pipe, 0.75 m long. At the top coil, droplets of liquid ammonia were created by a 6 mm OD tube, which was pointed to the top coil. The shell was equipped with three sight glasses. Thus, evaporation process could be observed.

There were two 1-inch pipes connected at the top and bottom of the shell. The bottom pipe allowed the evaporated ammonia and the auxiliary gas to be drawn into the absorber. This pipe also allowed the unevaporated water, which was carried in with liquid ammonia, to return back to absorber. The other pipe allowed the warm auxiliary gas from the absorber to return back to the evaporator.

3.5 The absorber

There are several types of absorber e.g. packed column, spray column, and falling film column. A falling film column was chosen because of its low-pressure drop and simplicity in construction. The need of an external heat exchanger and a circulation pump were eliminated as well. Theories of the falling film absorption process are given in several textbooks. A design procedure of a falling film absorber taken from the text book is as follows [Treybal 1968].

The change in concentration over a given length of falling film is,

$$\frac{\delta V_{avg}}{L}\left(C_L - C_O\right) = k_{l,avg}\left(C_i - C\right)_{avg} \tag{3.1}$$

The average concentration change in the right hand side could be obtained from a logarithmic average value as,

$$(C_i - C)_{avg} = \frac{(C_L - C_O)}{\ln\left[\frac{(C_i - C_O)}{(C_i - C_L)}\right]} \tag{3.2}$$

where

$k_{l,avg}$	average mass transfer coefficient ($m \cdot s^{-1}$)
V_{avg}	average film velocity ($m \cdot s^{-1}$)
L	length of wet wall (m)
δ	film thickness (m)
C	ammonia concentration ($kmol \cdot m^{-3}$)
C_O	ammonia concentration at the beginning of the wall ($kmol \cdot m^{-3}$)
C_i	ammonia concentration at liquid vapor interface ($kmol \cdot m^{-3}$)
C_L	ammonia concentration at the end of the wall ($kmol \cdot m^{-3}$)

The average film velocity could be calculated from:

$$V_{avg} = \frac{\Gamma}{\rho\delta} \tag{3.3}$$

The film thickness,

$$\delta = \left[\frac{3\mu\Gamma}{\rho^2 g}\right]^{1/3} \tag{3.4}$$

The mass transfer coefficient depends on contact time of liquid and vapor. The contact time is long when the flow rate is small or the film Reynolds number ($Re=4\Gamma/\mu$) less than 100. For long contact time,

$$k_{l,avg} = 3.41\frac{D}{\delta} \tag{3.5}$$

For short contact time,

$$k_{l,avg} = \left[\frac{6D\Gamma}{\pi\rho\delta L}\right]^{1/2} \tag{3.6}$$

where

Γ	mass flow rate per unit width ($kg \cdot m^{-1} \cdot s^{-1}$)
μ	viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
D	molecular diffusivity ($m^2 \cdot s^{-1}$)
ρ	liquid density ($kg \cdot m^{-3}$)

Height of the wall could be calculated by dividing it into a series of incremental lengths and assuming isothermal condition over each increment. The concentration entering and leaving each increment could be determined by using equations (3.1) to (3.6).

The constructed absorber consists of an internal vertical column on which solution formed a liquid film. The film would be created as the solution passed through a small gap at the top of the column. The surface of the column was cooled by the circulation of cooling water inside the internal column. The internal column was a 0.7 m long 4-inch pipe. This provided an external surface area of 0.25 m^2. The absorber shell was a 1 m long of a 6 inch pipe. Three sight glasses were used for observation of the absorption process. Two 1 inch pipes were used to connect the absorber's shell to the evaporator.

3.6 The bubble-pump system

The bubble pump system consisted of a pump tube, a generator, and a liquid vapor separator. The vapor generator was a horizontal shell (0.35 m long, 4-inch pipe). Heat input was supplied by a 4 kW electric heater. The pump-tube was attached to the top of the shell. The vapor, which was driven off from the solution, entered the pump tube and formed series of bubbles. The bubbles pushed the liquid solution, which entered via the liquid-inlet-tube, as shown in the schematic diagram, up through the pump tube. The liquid-inlet-tube was inserted into the generator, so that only liquid was allowed to enter. At the top of the pump tube, liquid solution dropped and accumulated in the separator before returning back to the absorber while the vapor rose up to the rectifier. The separator was constructed from a 0.35 m long of 4-inch pipe. It was equipped with a 4 kW immersion heater, which could be used to generate additional ammonia vapor. The use of two heaters (one in the generator and the other in the separator) provided more flexible operation as it allowed the liquid and vapor flows rate to be controlled separately. However, in this study, the second heater was not used.

3.7 The rectifier

Normally, ammonia vapor exiting the pump tube is not pure. It contains some amount of water, which is evaporated with ammonia. If this water is allowed to liquefy in the condenser, it will enter the evaporator and cause the evaporator temperature to increase (at a given pressure, ammonia evaporates at a higher temperature with increased amount of water). In order to maximize the system performance, the ammonia vapor must be purified before entering the condenser. To purify the vapor, it must be cooled down to a certain temperature in a rectifier. Thus, only pure ammonia can enter the condenser as the water is condensed and dropped back to the separator. The rectifier used here was designed based on a shell and coil type heat exchanger. The shell was a 0.4 m long 3inch pipe. The internal cooling coil, through which cooling water was circulated, was made from 6m of 10mm OD tube and provided total surface area of 0.19m^2.

3.8 Helium reservoir

The helium reservoir was constructed from a 0.25 m long 6 inch pipe. It was located at the highest position and was connected to the evaporator and the condenser by two vent tubes (6mm OD). The helium reservoir allowed the helium to expand when the condenser temperature and pressure increased. The vent tubes also allowed the evaporator pressure and the condenser pressure to be equalized.

3.9 Thermal insulation

To reduce unwanted heat losses from the system, hot components (generator, pump-tube, rectifier, solution heat exchanger, and pipe line) were insulated with 30 mm thickness of glass fiber wool with aluminum foil backing. To prevent unwanted heat gains to the system, the evaporator was covered with rubber foam insulation. The condenser was also insulated with rubber foam, so that its condensation temperature could be kept as required. The absorber, the helium reservoir, and the rectifier were left uncovered.

3.10 Hermetic seal test

The feature of this experimental refrigerator was that it could be easily dismantled for modification. This resulted in the use of many removable joints and gaskets. The system was tested hydrostatically to 40 bar. To ensure leak proof, the system was tested with compressed nitrogen to 20 bar.

3.11 Working fluids

Diffusion absorption system uses three working fluids. Ammonia (NH_3) and water are used as refrigerant and absorbent respectively. For a commercially available refrigerator, hydrogen (H_2) is used as auxiliary gas. However, in this experiment, helium was used instead of hydrogen for reasons of safety.

Ammonia and water solution with concentration of 0.25 was prepared in a separated vessel as shown in figure 3.3. The vessel was initially filled with 7 liters of distilled water. Before the vessel was charged with ammonia, the air inside was evacuated by using a vacuum pump. The concentration was calculated by weighing the vessel containing solution.

The experimental refrigerator was evacuated before charging the prepared-solution. Then the solution was charged to the absorber. After the system was charged with ammonia-water solution, the system pressure was recovered. Then it was charged with helium until the required pressure was obtained.

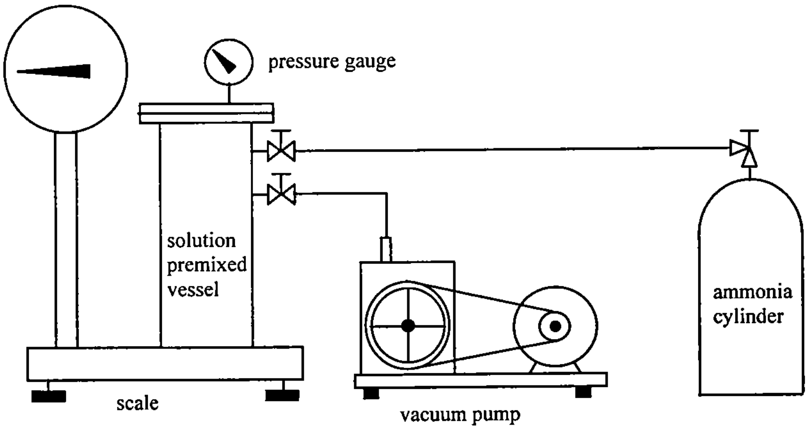

Figure 3.3 A set up used to prepare ammonia-water solution.

3.12 Instrumentation and control

Variables to be measured and controlled were temperature, pressure, flow rate, and electric power input. Control and data logging were provided by a personal computer with data acquisition system (ADAC 5525MF). It was arranged so that the operating temperature and pressure could be pre-set and controlled.

Type K thermocouple probes were used for measuring fluid temperature at various locations as shown in Figure 3.2. Each probe was connected to a thermocouple amplifier with an output of 10 mV/°C. Each was calibrated using a precision thermometer.

System pressure could be measured by using a dial compound gauge (-1 to 24 bar). A pressure transducer (0 to 60 bar) with signal output of 0 to 10 V was also used for more precise measurement. It was calibrated using a standard dead-weight tester. The signal output was sent to the computer.

The generator's and the separator's temperatures were controlled by adjusting their power of respective heaters (using computer controlled solid-state relays). The electrical power input to each heater was measured using a power transducer. Each transducer was calibrated using a digital power meter.

Temperature of the cooling water was maintained between 30 and 32°C throughout the tests. Temperature of vapor ammonia exiting from the rectifier was controlled using solenoid valve to on/off the cooling water.

3.13 Conclusion

The details of design and construction of the experimental refrigerator are described. Heat input to the system was provided by means of an electric heater. This allowed the power input to be controlled and recorded conveniently. The system was constructed so that each component could be analyzed individually.