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Abstract	The temperature of Photo-Voltaic (PV) cells which increases when getting high radiation levels during the mid-day can reduce the efficiency of PV cells. This is a detrimental characteristic of producing electrical energy in a solar power generation system. The study objective is to improve cooling techniques in PV cell installations, particularly to maintain the temperature condition of the system working at optimal performance. The research was carried out using an experimental method by conditioning the PV module under vacuum pressure (pressure < 1 bar). A casing is designed in such a way as to allow a PV cell to be in a negative condition with sunlight still being able to penetrate it on the top side by using a material that is translucent and can withstand negative pressure. Nitrogen gas is filled into the casing before being vacuumed at negative pressure. The test is carried out outdoors with the actual conditions of solar radiation and ambient air temperature. Parameters for measuring pressure, temperature, radiation level, voltage, and current as well as electric power use an instrument equipped with a data logger that measures in real-time with a high degree of accuracy. The type of PV module employed in the test consists of two mono-crystal PV modules. One PV was treated with vacuum pressure while the other was left under normal conditions. The test results show that the temperature of the PV cell in a vacuum has a slow increase, where the maximum temperature is 30 °C even though it gets a high level of radiation during the day. There is also a difference in efficiency between those treated with negative pressure compared to PV cells that was not treated.

Keywords	Cell PV - Vacuum pressure - Cooling technique - Temperature

(separated by '-')

The Vacuum Technique for Cooling PV Cell

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Abstract. The temperature of Photo-Voltaic (PV) cells which increases when getting high radiation levels during the mid-day can reduce the efficiency of PV cells. This is a detrimental characteristic of producing electrical energy in a solar power generation system. The study objective is to improve cooling techniques in PV cell installations, particularly to maintain the temperature condition of the system working at optimal performance. The research was carried out using an experimental method by conditioning the PV module under vacuum pressure (pressure < 1 bar). A casing is designed in such a way as to allow a PV cell to be in a negative condition with sunlight still being able to penetrate it on the top side by using a material that is translucent and can withstand negative pressure. Nitrogen gas is filled into the casing before being vacuumed at negative pressure. The test is carried out outdoors with the actual conditions of solar radiation and ambient air temperature. Parameters for measuring pressure, temperature, radiation level, voltage, and current as well as electric power use an instrument equipped with a data logger that measures in real-time with a high degree of accuracy. The type of PV module employed in the test consists of two mono-crystal PV modules. One PV was treated with vacuum pressure while the other was left under normal conditions. The test results show that the temperature of the PV cell in a vacuum has a slow increase, where the maximum temperature is 30 °C even though it gets a high level of radiation during the day. There is also a difference in efficiency between those treated with negative pressure compared to PV cells that was not treated.

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1 Introduction

Renewable energy sources are becoming increasingly popular, especially when associated with pollution and the depletion of conventional energy reserves. With the increase in the human population, the question arises, what will be the next reliable source of energy after the loss of fossil fuels. One of the most abundant resources is solar energy, which is directly as solar radiation, or indirectly as wind energy and biomass energy.

There are two types of energy that can be obtained from direct solar radiation, namely electrical energy and thermal energy. The most efficient way to get electrical energy from direct sunlight is through photovoltaic cells (PV cells). Roughly the efficiency of PV cells on the market, the maximum ranges from 11%–20% [1–3].
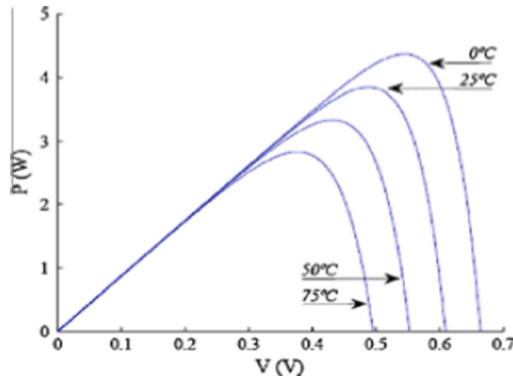
Fig. 1. Characteristic of PV cell as function of temperature refer to the author [5]

The efficiency characteristics of photovoltaic cells tend to decrease drastically with increasing temperature, especially at high levels of solar radiation or at peak conditions. The rate of reduction ranges from 0.25% to 0.5% per degree Celsius, depending on the cell material used [4]. The relationship between power (P) and voltage (V) of the PV cell with the influence of temperature varying from 0 to 75 °C can be seen in Fig. 1, which adopts the results of the research conducted by the author [5]. The maximum power of a solar cell decreases with increasing cell temperature at the same radiation level.

Another researcher (Daniel Tuddor/6) also found that the power was reduced by 0.47% for an increase in cell temperature of 1 °C when given the same radiation level in a PV cell. In addition, high temperatures can reduce the economic time of the PV system. These things are a fundamental problem in the solar PV power generation system which can reduce electricity production quite significantly.

As an illustration, for each a solar PV power generation installation that has an installed power capacity of 1 MWp. At peak conditions, the decrease in efficiency reaches an average of 7% for 3 h (in the tropics it usually occurs from 11 am–13 pm) with the module temperature reaching 35 °C, the decrease in electricity production ranges from $(0.07 \times 1000 \text{ kW} \times 3 \text{ h}) = 210$ kWh per day, or about 76,650 kWh per year, or the equivalent of 7650 USD/year (assuming the price of electricity is 0.01 USD/kWh). Furthermore, it can be estimated that greater losses if the PLTS plant installation has an installed capacity of 10 MW or multiples thereof. Even in desert areas where PV mini-grid installations are now being placed, the decrease in efficiency can be even greater because the increase in PV cell temperature can reach 54 °C during the day.

This study aims to obtain a cooling method that can maintain the ideal temperature of the PV cell in optimum conditions with a new method, namely the application of the negative pressure casing technique by adopting cold mountain conditions even though it is snowing even though it gets heat radiation compared to lowland areas.
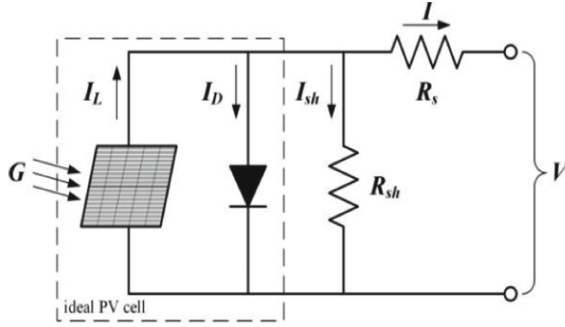
Fig. 2. A Photo Voltaic Modeled.

2   The Art of Study

A photovoltaic cell can be modeled as in Fig. 2. Mathematically the PV cell circuit can be formulated as in Eq. (1), referring to the author [7], as follows,

$$I = I_L - I_o\left(e^{\frac{V+IR_S}{V_T}m} - 1\right) - \frac{V + IR_S}{R_S} \tag{1}$$

Where $VT = kT/q$ as the thermal voltage, T is the temperature module, k is Boltzmann's constant, and q is the number of elementary electrons. From Eq. (1) it shown that the current I is inversely proportional to the temperature. While the temperature of the T module can be calculated theoretically using the following equation [8],

$$T = T_{amb} + (NOCT - 20)G/800 \tag{2}$$

Where temperature module (Tm), ambient temperature (Tamb), and solar radiation level (G) while NOCT can be written accordingly,

$$NOCT = 20\,^{\circ}C + T_{Rise}$$

Therefore, the temperature module is a function of radiation level, ambient temperature, and NOCT. In experiments using precision measuring instruments, Eq. (2) only has an error of 5% [4].

The effect of temperature on a PV material is defined as the temperature coefficient. For polycrystalline PV panels, for example, if the temperature drops by one degree Celsius, the voltage increases by 0.12 V and vice versa, so the temperature coefficient is 0.12 V/°C. The general equation for estimating cell voltage at a particular temperature is as follows;

$$V_{OC,new} = 0,12\left[V/_C\right] x \,(25\,(^{\circ}C) - T_{ambient}\,(^{\circ}C) + V_{OC,rated}\,(V) \tag{3}$$

$$T_{ambient}\,(^{\circ}C) = module\ temperature$$

$$V_{OC,\,rated} = Open\ circiut\ voltage\ at\ STC$$

$$\left(\text{Standard Test Condition} = 25\,°C\right)$$

The PV cell efficiency (η) is calculated using the following equation:

$$\eta = \frac{P_{max}}{G \times A} \tag{4}$$

Where A is the area of the photovoltaic cell, Pmax is the power generated by the PV cell, and G is the radiation level. Because the increase in the temperature of the PV cell can reduce the efficiency of the cell, efforts need to cool the cells to optimize electricity production. Recently, various cooling techniques have been carried out to reduce cell temperature.

There are two types of cooling cell PV. They are categorized as follows: 1) active cooling, which consumes energy 2) passive cooling, which uses natural convection/conduction to activate heat extraction. Both types of PV module cooling techniques have their respective advantages and disadvantages.

Passive cooling techniques can be divided into three categories, 1) passive air cooling, 2) passive water cooling, and 3) conductive passive cooling. Conductive passive cooling mostly ends in passive air cooling, but the difference is that the prevailing heat transfer mechanism of the PV cell is conductive. Cuce et al. [9] conducted experimental studies on polycrystalline PV cells under controlled conditions. Two PV Cells are employed: one with aluminum fins as a heat sink, with thermal grease, and one without a heat sink. Illumination varies from 200 to 800 W/m². The increase in electrical efficiency were 9% compared to those who did not receive cooling treatment. While R. M. Hernandez et al. [10] who studied the depth of the flow channel under the PV cell obtained that there was a significant effect on passive cooling. The results show that the temperature of the PV module is 5–6 °C lower than that of the PV module that is not water-cooled.

Passive cooling techniques can be split into three categories, 1) passive air cooling, 2) passive water cooling, and 3) conductive passive cooling. Conductive passive cooling is a particular type of passive conductive cooling that employs the cooling of a phase change material (PCM). The authors [11] have reported that, with the right type of PCM material, a reduction of 5 °C compared to the reference PV cell can be reached for a period of 5 h at a radiation level of 1000 W/m². A PV module with a nominal power of 65W is used, with a 50 mm thickness PCM placed on the underside of the PV, with vertical aluminum fins to improve conduction. The advantage is higher power by 1% compared to reference PV modules.

Several studies of the passive water cooling have been carried out with cooling on front and back surfaces of PV. Rosa-Clot et al. [14] used a submerged technique to cool a monocrystalline PV module in water. The effect had limited success: the temperature was maintained at 30 °C which resulted in a relative efficiency increase of 2%, but the intensity of radiation reaching the PV cell decreased with depth. However, at a depth of 4 cm, the relative efficiency increased by 1.1%. El-Seesy et al. [15] tried to cool PV cells by thermosiphon effect. A polycrystall silicon module, with a total area of 0.260 m² was employed, along with copper sheets and tubes mounted on the back of the module and a thermosyphon water system with a water capacity of 80 L. The relative efficiency increase was 1.9%. Chandrasekar et al. [16] used a capillary effect to cool the

back of the monocrystalline PV Module. The capillary effect is generated through the spirally wrapped cotton wick structure on the back of the module, and immersed in the liquid. Capillary liquid nano cooling was also tried, but failed to increase the cooling effect when compared to water. The maximum efficiency increase reaches 1.4% when compared to the non-cooled module.

Active cooling method. This method can be considered a continuous power-consuming method to cool the PV modules. Most of the methods used are based on air or water cooling. Therefore, the most energy consumption system is pumps or fans in order to keep the liquid circulating. The active cooling methods result in more power generation and accessible heat energy, but power consumption is also required.

Theo et al. [19] studied to cool four polycrystalline PV modules with forced air from the rear side. The surface area of the PV module is 0.78 m^2. Custom flow channels are created and CFD analysis is utilised to optimize their shape. The total efficiency gain is about 1%, depending on the irradiation compared to untreated PV. The optimal airflow under the panels is 0.055 kg/s, although no ambient temperature is given. Therefore, this information is reliable only for particular cases. However, this information can be valuable when trying to evaluate the amount of air required to cool a standard PV module. Farhana et al. [20] used a 0.924 m^2 polycrystalline PV cell with the air-cooling effect. Two cells were compared, one without cooling. The cooler is an aluminum casing on the back side acts as a flow channel. The mass flow of air is about 0.035 kg/s. The results show a maximum relative increase in efficiency of 8.9% and a maximum temperature decrease of 12 °C. Other authors [10] have shown that, for an air mass flow of 0.74 m^3/s, the total PV efficiency can be maintained above 13.5% at peak radiation of 970 W/m^2. Arcuri et al. [21] cooled a 1 m^2 polycrystalline PV panel with forced air. Cooling is on the back side of the panel via a specially constructed flow channel. The flow channel consists of a 1 mm thick sheet aluminum at the back of the plate and a wooden casing around it. An average mass air flow is about 0.016 kg/s. Air mass flow is created through a helical fan with a power consumption of 3.6 W. The average increase in total efficiency is about 0.6%, depending on the radiation level.

As for forced water cooling, two different techniques can be applied: front side and back side cooling. Hosseini et al. [22] made a thin water film on the front side of the monocrystalline PV panel and obtained a total efficiency increase of about 1%. The total area of the panels is 0.44 m^2 while the maximum water discharge is about 1 L/minute. The pump used consumes 0.25 hp. A temperature drops of 12 °C is achieved. There is no mention of the amount of heat released by evaporation, which must be taken into account when cooling is carried out from the front side. Dua et al. [23] used 0.152 m^2 concentrated monocrystalline PV cells. The cooling technique used is cooling the back side through 2 aluminum pipes. The peak efficiency gain is 0.8% for a mass flow of 0.035 kg/s water. The peak temperature of PV is about 60 °C. Bahaidara et al. [24] studied cooling a 1.24 m^2 monocrystalline PV module from the back side through a closed casing through which water flow. The water pump consumes 0.5 HP of power. The maximum mass flow is 0.06 kg/s. The maximum efficiency increase compared to non-cooled modules is 2.8%, and the module temperature reduction average 10 °C.

Based on the reference above, the research that has been carried out using a passive method has not been able to reduce conditions below the ambient air temperature.

Meanwhile the forced method, the PV cell temperature can be lowered slightly below the ambient air temperature but consumes power hence the efficiency of the system to produce electricity does not change much. From the research results that have been reported, the forced cooling using water is better than other methods, but when the required power is taken into account, the net gain in electricity production is relatively small. Another thing that is most difficult for water cooling when it is applied in desert areas that lack water.

3   Methodology

The temperature of the mountains with an altitude above 6000 m above the earth's surface is lower. Their surfaces always is covered by ice such as on the Himalayas and some mountains in the world. In fact, the radiation received in such a place is higher than radiation in the lowlands. The decrease in temperature in mountainous areas is caused by low pressure. The pressure decreases with the height of a location above the earth's surface.

The PV cell cooling technique offered here adopts mountainous conditions by applying pressure around the PV module under atmospheric pressure (negative pressure). This technique can be categorized into passive cooling types hence it does not require continuous power for the working process. Theoretically, if the pressure drops at a constant volume, then the air temperature will drop following Gay Lussac law's equation. Mathematically Gay Lussac's law can be written as accordingly,

$$\frac{P}{T} = k \tag{5}$$

Where P is the absolute pressure of the gas or air, T is the absolute temperature of the gas, and k is the gas constant. In simple terms the Eq. (5) can be written as follows:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \tag{6}$$

Where subscripts 1 and 2 refer to initial and final gas states in the system. The pressure and temperature are all in absolute conditions, hence the pressure gauge (Pg) can be written as,

$$P_g = P_{abs} + P_{atm}$$

Where subscripts 1 and 2 refer to initial and final gas states in the system. The pressure and temperature are all in absolute conditions, hence the pressure gauge (Pg) can be written as,

$$P_g = P_{abs} - P_{atm}$$

Therefore, the Gay-lussac equation can be written as the following equation,

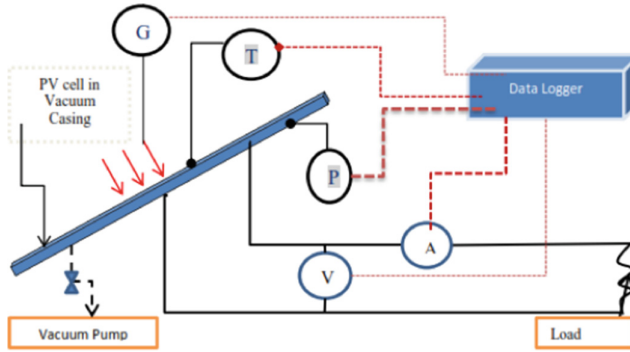$$P_{g2} = \frac{(P_{g1} + P_{atm})T_2}{T_1} - P_{atm} \tag{7}$$

Fig. 3. The Schematic diagram of experiment.

$$T_2 = \frac{(P_{g2} + P_{atm})T_1}{P_{g1} + P_{atm}} \tag{8}$$

From Eq. (8), if the pressure of a room is lowered (Pg2), it will cause the room temperature to decrease (T2). Hence if the PV cell is placed in a low-pressure room, the effect of radiation level does not affect much as written in Eq. (2) and Eq. (8).

3.1 Experiment Set Up

Two PV modules of the mono facial monocrystalline modules with certain specifications will be employed. The schematic diagram of the experimental research is shown in Fig. 3.

Two PV modules were used in this experiment. One PV cell is in the vacuum condition and the other one left in normal conditions as a reference.

There are pressure, solar radiation and temperature sensors to measure the pressure of the vacuum, radiation intensity and the temperature of the PV cell. Voltage, current, and solar radiation are measured in real-time using a data logger to ensure accurate measurement results.

The casing design is shown in Figs. 4 and 5. The casing frame is made of board material with a thickness of 18 mm. The size of the casing adjusts to the dimensions of the PV. The casing is utilised with a valve to allow air to be sucked from the casing by a vacuum pump. The top of the casing is covered with glass with a thickness of 5 mm type borosilicate glass which is strong enough to withstand negative pressure. There is a pressure sensor mounted on the casing to measure the pressure conditions in the PV casing chamber. The data sampling experiment took place from 9:00 a.m. to 3:00 p.m. Both PV modules are placed outdoors in the same position.

Measurement of ambient air and surface temperature distribution of the PV module is made possible by the presence of a temperature sensor that monitors evenly on the top and bottom surfaces of the PV module. The results are collected and recorded using a Temperature Logger. The output voltage and current are also carefully monitored in real-time during the test.

At the same time, experiments were also carried out on PV modules without negative pressure treatment. The condition of the level of solar radiation and the ambient air
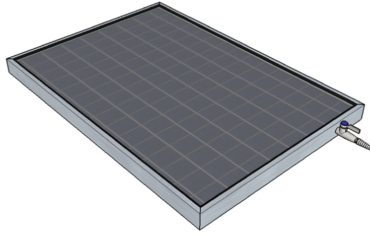
Fig. 4. The casing frame for PV cell
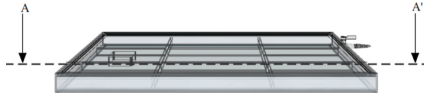
Fig. 5. PV cell with the casing.

temperature was the same as the experiment that received the negative pressure treatment. Those make it possible to compare the temperature response of the two PV modules. It is also possible to compare PV efficiency by monitoring the electricity generated, including the output voltage and current.

4   Results

The experiment was carried out on 2 PV panels, where the one PV is in a vacuum pressure condition of 0.5 bar, and the other one is in a atmospheric pressure condition.

Figure 6 shows the ambient air temperature at the time period of the experiment was around (35–36)°C, at a pressure of 1 atmosphere. The weather in the location, namely Makassar City, South Sulawesi Province, Indonesia, were very bright in high radiation levels ranging from 700 w/m^2 to 950 w/m^2, as shown in Fig. 7.

Likewise, the current generated by the panel under vacuum pressure is greater than the current generated by the PV panel at normal atmospheric pressure. It shows in Fig. 8, where the current generated by the PV panel at a pressure of 1 atm only ranges from 0.625 amp, while the output current at the panel under vacuum conditions is in ranges from 0.89 amp to 0.91 amp.

There is a difference in the surface temperature of the panel under vacuum with the surface temperature of the PV panel under normal conditions (atmospheric pressure). The difference in temperature difference is quite significant. Figure 6 shows the upper surface temperature of the PV panel under normal pressure conditions ranging from (44–45)°C, while the temperature at the top surface of the PV panel under vacuum pressure is in the ranges from (29–30)°C as shown in Fig. 7. These is consistent with the Gay Lussac theory, where the ratio of pressure and temperature tends to be constant. As the pressure air drops in the casing, so does the temperature.

Figure 8, shows the temperature on the top surface of a PV panel under normal condition at atmospheric pressure. The effect is that the PV cell temperature affects the electricity production produced by both panels with the same radiation level. The electricity production produced by PV panels under vacuum is greater than the electricity produced by PV panels under normal conditions. This is in accordance with the results of several previous researchers [5], that an increase in temperature reduces the efficiency of PV cells.

In Fig. 9, it can be seen that the average output voltage of the panel under vacuum is more than 18 V, while the output voltage of the panel under atmospheric pressure is on average 16.75 V, as shown in Fig. 10 (Figs. 11 and 12).

[AQ2]
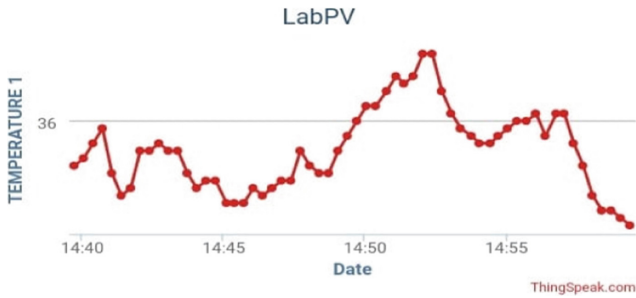
Fig. 6. The surrounding air temperature.
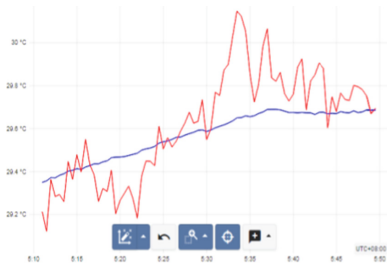
Fig. 7. PV under vacuum (0,5 bar)
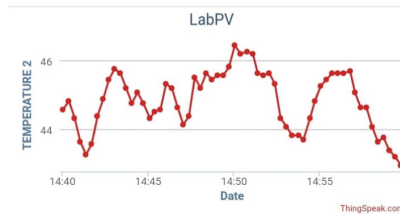
Fig. 8. PV in vacuum (0.5 bar)
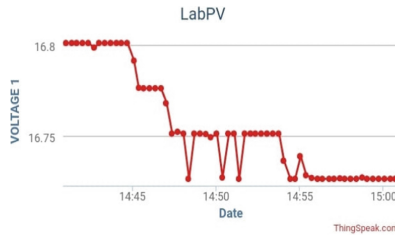
Fig. 9. The PV in normal condition, 1atm
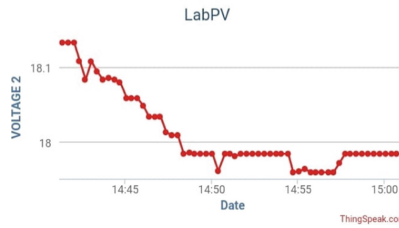

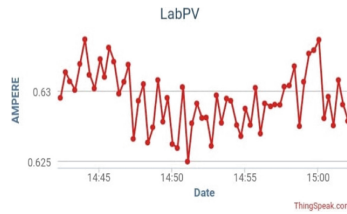**Fig. 10.** The PV vacuum (0,5 bar)
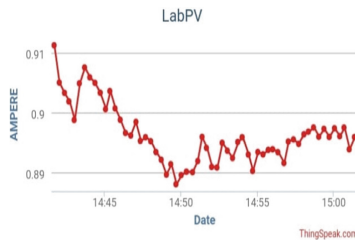
Fig. 11. The PV output current 0,5 bar

Fig. 12. The PV output in normal conditions

5   Conclusion

The PV cell cooling technique has been carried out by conditioning the panels in a vacuum condition to apply Gay Lussac's law. The experimental results show that the PV cell temperature which is exposed to high intensity solar radiation can be reduced

because the object is in a vacuum medium. Therefore, in conditions of high radiation levels, the efficiency of the PV cell can still be maintained to work optimally. With this cooling method, the temperature of the PV cell can be lowered below the ambient air temperature. The additional investment cost for conditioning PV cells under vacuum will be evaluated in the next study.

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Chapter 13

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