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Experimental study for natural gas production from hydrate reservoir by electric heating method

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Abstract: In this study, an experimental apparatus has been designed and set-up to analyse the dissociating phenomena of hydrate in porous rock using electric heating method supplied at downhole. The electric heat injecting experiments have been performed to investigate the heat transfer within the core, the dissociating phenomena of hydrate, and the productivities of dissociated gas and water. These experiments were under constant heat injecting method as well as preheating methods. From the experimental results, it is seen that the hydrates is dissociated along the phase equilibrium curve and dissociation of hydrate is accelerated with heat. The injected heat is consumed for the dissociation and also it is lost together with outflow of the dissociated gas and water. From the investigation of gas producing behavior for various heat injecting methods, as the injected heat is greater, dissociation is accelerated faster at outlet and hence the initial gas production becomes higher. Also, it is shown that the initial gas productivity under the constant heating method is better, however, the energy efficiency is low because of smaller amount of the produced gas comparing to the amount of heat injected. In the experiments of preheating method, it was seen that gas production only initial stage is different with the preheating time, but the producing behaviors of gas production are similar.

1. Introduction

There are three schemes for producing the gas from hydrate gas reservoir. Firstly, thermal method was proposed by Bayles et al (1986), Kamath and Godbole (1987), and Selim et al (1990). Secondly, depressurization method was proposed by Verigin et al (1986) and Yousif et al (1990, 1991). The above methods are changed the reservoir temperature or pressure below equilibrium condition in order to dissociate hydrates. Finally, the injecting of the chemical additives like methanol is proposed to change the equilibrium condition (Sung et al, 2003). The depressurization method is the most economic because there is no need for external source of energy comparing to thermal method but it has deficiency to dissociate slowly. Although the dissociation of hydrate is accelerated with injecting of the chemical additives, the economical efficiency is low because the sweep efficiency of chemical additives to reservoir at the initial production stage is low due to the low permeability of hydrate gas reservoir and the cost of chemical additives is expensive. Therefore, the productivity of hydrate gas reservoir is improved by depressurization method accompanying thermal method because the dissociation of hydrate is accelerated with thermal method and dissociated gas was produced by depressurization method. Thermal method in the conventional heavy oil reservoir is usually conducted by hot brine or steam injection. But, the hydrate gas reservoirs are mostly existed in permafrost regions or deep ocean and so this method has a defect of energy loss to the surroundings or wellbore. Hence, it is a effective that electric heating equipments were setting at the bottom of wellbore to minimize the heat loss. In this study, an experimental apparatus has been designed and constructing to perform experiments of hydrate in porous rock by electric heating method. With the aids of the developed experimental model, the efficiency of the injected electric power and the heat transfer of the core and the dissociating phenomena of the hydrate by electric heating are investigated. Also, it is investigated that the flowing behavior of the dissociated gas and water in porous rock and the efficiency of the production with various injecting methods.

2. Setup of Experimental Apparatus

The schematic diagram of the experimental apparatus system is shown in Fig. 1. The coreholder as main part of the whole system is made of sus 316 to stand high temperature and pressure condition. Inlet and outlet of the core are hold by end plugs and the lateral face of the core is fixed by viton sleeve by confining pressure, which allows the flow only in an axial direction. The utilized fluid for yielding confining pressure is kerosene because it has low electrical conductivity and the 95% purity of kerosene is used in this experiment. As shown in Fig. 2, the three pairs of resistance port were installed to indicate indirectly the formation of hydrate and RTD sensor ports was placed to measure inside of the core temperature at 2.5 cm interval from the center of core. Also, RTD sensor ports were installed to measure both ends of core temperature at the end plug and four heaters in outlet end plug were inserted to generate heat by electric power. The injecting electric power and temperature of the heater are controlled by the transformer which is 45V ~ 220V changeable. In this experiment, porosity and permeability of the berea sandstone are 24% and 218 md respectively, and length and diameter of the berea sandstone are 15.4 cm and 3.76 cm. The coreholder is immersed in a water bath controlled by the refrigerated circulator to control the temperature during the formation and dissociation of hydrate. This experiment is used the methane gas as hydrate former with its quality of 99.995% of methane (Air Products Co.) and brine as a solid lattice constructor with content of 1.5 wt% of sodium chloride. The data acquisition system records pressure, temperature, electrical resistance, and gas production rate. These parameters were calibrated using pressure test gauge with sub dimension of 2 psi, mercury thermometer with tolerance of ±0.01K, resistors with standard resistance of 2~10 kΩ, and wet gas meter having capacity of 1000 cc/revolution and sub dimension of 10 cc, respectively.

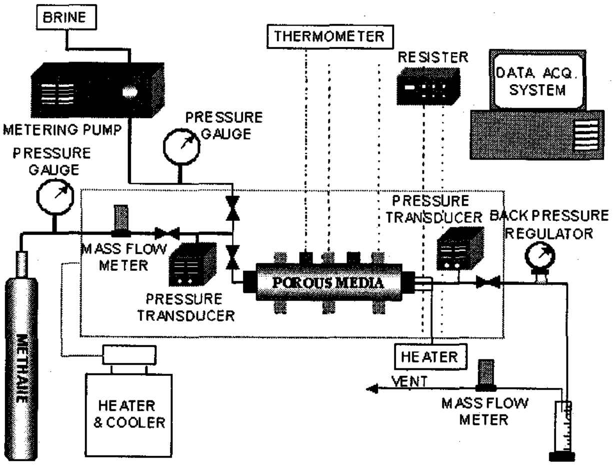


Fig. 1. Schematic diagram of total system.

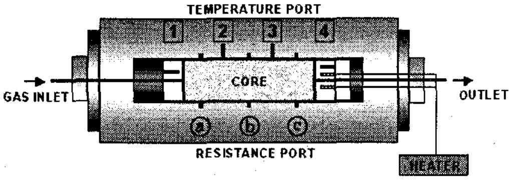


Fig. 2. Schematic diagram of coreholder.

3. Experimental Results

Forming Experiment

The hydrate formation experiment was performed to investigate dissociation of hydrate by electric heating method. The procedures of formation experiment were as follows: First, the core is placed in the core holder and pressurized externally with confining pressure of about 1.38 MPa. Then the system was evacuated to remove impurities by vacuum pump. The 1.5 wt% NaCl solution and methane gas are circulating up to obtain the desired saturation. The initial water saturation in this experiment is set to 0.71. Methane gas is injected with pressure high enough to accelerate to forming hydrate. When there is no more pressure change, it is considered that the formation is complete. The analysis of pressure behavior is important because formation experiment is performed at constant temperate. The pressure at the stage of formation is decreased in constant volume system because the free gases are entrapped by hydrate lattice and reversely, the pressure is increased as the hydrate is dissociated. Also, the resistance behaviors are important because the electric resistance of hydrate is high like ice rather than that of the saturated rock with sodium chloride solution. Therefore, the resistance is relatively increased as the hydrate is formed. The measured pressure and resistance from the experiment by above procedures are shown in Fig. 3. From this figure, it is observed that pressure decreased to 2.76 MPa from the injection pressure of 5.3 MPa and electric resistance increased in maximum value of 17.7 kΩ as hydrate is formed.

After forming step is finished, annealing process is conducted to form hydrate sufficiently by increasing gas-water contact and to make uniform hydrate distribution along the core. In annealing processes, the temperature is increased to 279.16 K to dissociate hydrates and decreased again the temperature, 273.76 K, to form hydrates. This experiment is performed two cycles of an annealing process. Such an annealing process may also have occurred in nature through an extremely slow climate cycle (Yousif et al. 1991).

Heat efficiency of heat injection port

Before conducting the dissociating experiment by electric heating method in porous rock, firstly, heat efficiency of the injection port is investigated by measuring the temperature for various injected heating cases. The temperature of injection port is measured by changing the injected heat from 3.5 W to 85.7 W. The injected heat is controlled by electric power which is adjusted to 45 V, 50 V, 220 V as well as the number of connected heater which has four at most. Hence, this experiment has limits of heat energies from 3.5 W to 17.7 W.

The temperature of injection port and the total injected heat energy with heat power is shown in Fig. 4. In Fig. 4, it is seen that the temperature of injection port is linearly increased as the injected heat is increased. But, it is noted that the slope of the total injected heat energy start decreasing at 17.7 W unlike temperature slope. The energy for dissociating hydrate until 17.7 W is consumed more than that of rising temperature to injection port and core because the enthalpy of dissociation, 368,803 kJ/m^3 is bigger than the heat capacity of injection port, 3,600 kJ/m^3 and that of core, 1,627 kJ/m^3. Hence, the slope at the part of 17.7 W was decreased because the injected heat energy was used to increase the temperature of injection port and core since the hydrate is completely dissociated.

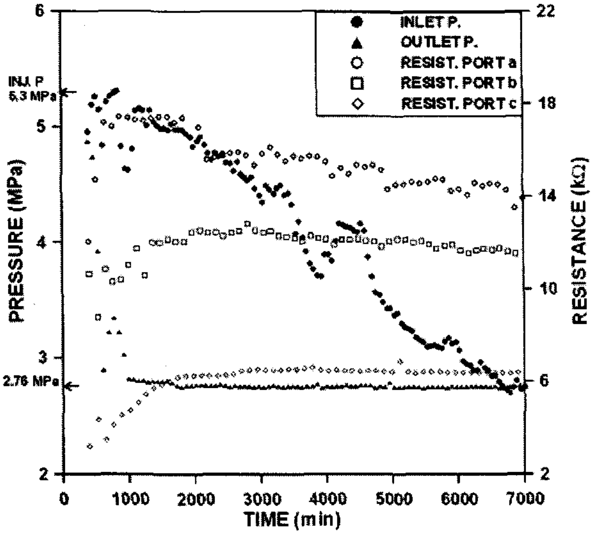


Fig. 3. Pressure and resistance behaviors during hydrate formation.

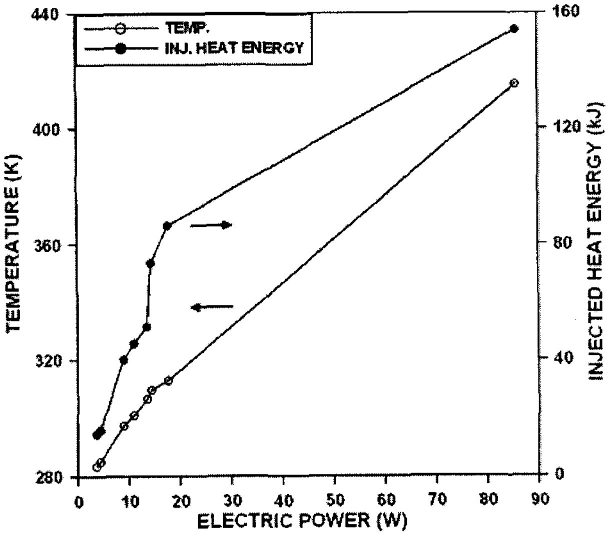


Fig. 4. Temperature and injected heat energy with electric power at heat injection port.

Heat transfer within core and dissociating phenomena

The RTD sensors as shown in Fig. 2 are placed at 5.1 cm and 10.3 cm from the injection port to investigate the heat transfer inside core according to injected heat energy. Temperature distribution is shown in Fig. 5. From this figure, the increase of temperature is large as the injection port is close and temperature is linearly increased as the injected heat energy is increased. Whereas the temperature of injection port is increased from 283.56 K to 415.12 K in Fig. 4, the increment of temperature of core is relatively small from 274.63 K to 283.29 K. This is explained by investigation to compare the injected heat energy with the actual consumed heat energy for increasing the temperature of core. The consumed heat energy for increasing the temperature of core is calculated from the thermal conductivity of the Berea sandstone, 0.0157 J/cm•s•K and the difference of temperature between injection port and the place of 5.1 cm apart from injection port. The consumed heat energy is calculated to 7.5% of the injected heat energy and so it is known that the only 7.5% of the injected heat energy is consumed for the rising temperature of core. Hence, the most of injected heat energy is used for increasing the temperature of injection port and kerosene wrapping core for yielding the confining pressure.

To investigate dissociation of hydrate by electric heating, the equilibrium pressure and average temperature of the core is presented together with hydrate equilibrium curve in Fig. 6 when the injected heat is 3.5 W, 4.3 W, 8.8 W, and 13.4 W, respectively. From Fig. 6, it is seen that the temperature and pressure at equilibrium is increased along the hydrate equilibrium curve as the injected heat energy is increased. Therefore, the dissociation phenomena by electric heating are coincided with the hydrate equilibrium line and at the same time, the developed experimental apparatus is validated.

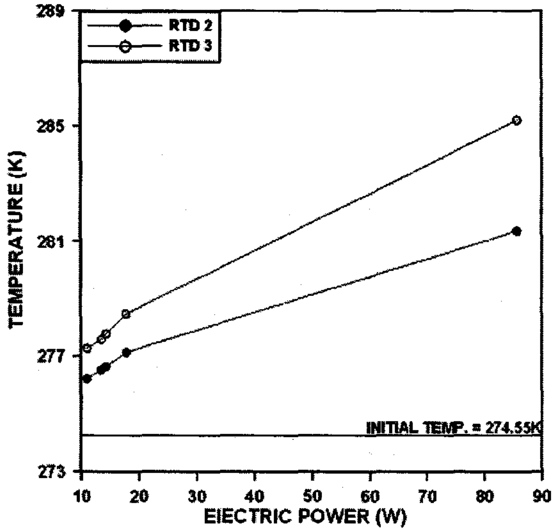


Fig. 5. The temperatures with electric power at port 2 and 3.

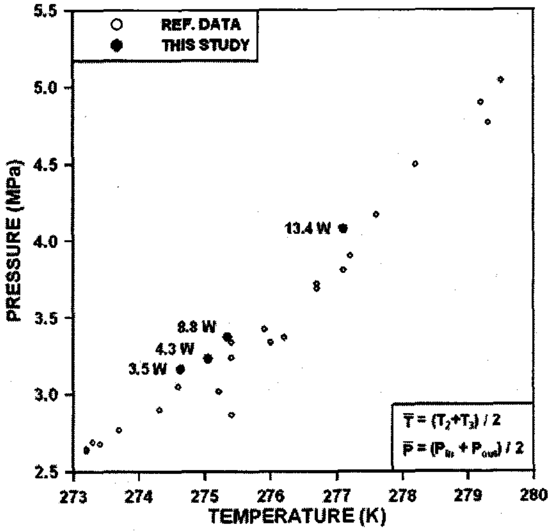


Fig. 6. The comparison of experimental data with the reference

Heat transfer with core and dissociation phenomena

It is reported that the temperature of injection well is sharply increased and the energy efficiency is low because of the heat loss to surrounding rocks when the heat is continuously injected in oil field. The step-wise injection method is proposed to improve the problems. Hence, the constant as well as step-wise injecting experiments have been performed to investigate the dissociating phenomena. From the step-wise injecting experiment, the temperatures of inside core and is shown in Fig. 7 and the pressure of both ends and the resistance behaviors of core shown in Fig. 8. Also, the average temperature of core before and after injection and the injected heat energy by constant as well as step-wise injection are listed in Table 1. The temperature behaviors by step-wise injection in Fig. 7 shows the same aspect in spite of injection method like as connecting the temperature by constant injection in Table 1. From the pressure and resistance behaviors in Fig. 8, the pressure of inlet is sharply increased when 8.8 W and 17.7 W is injected. It means that the gas is dissociated from the hydrate at the gas injection part.

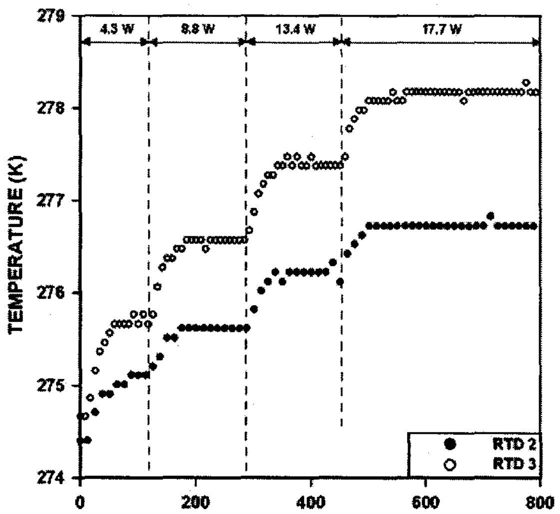


Fig. 7. Temperatures with time at port 2 and 3 under step-. wise heating method.

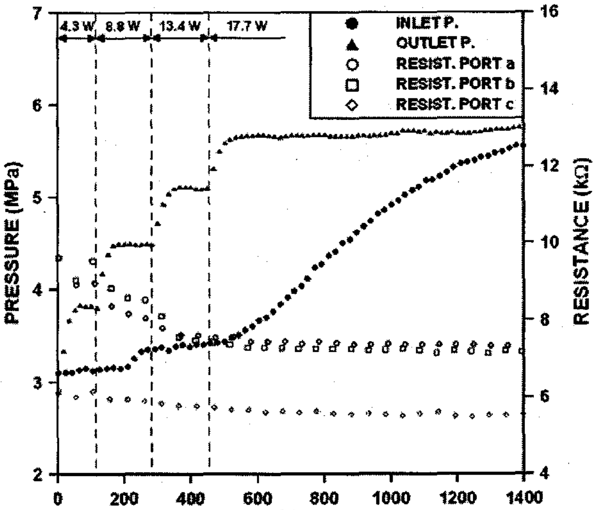


Fig. 8. Pressure and resistance with time at various locations under step-wise heating method.

To investigate the heat efficiency between constant and step-wise injection, the injected heat energy at the each step and cumulative injected heat energy by step-wise injection is compared with the injected heat energy by constant injection in Table 1. The final temperature of the each step is almost same to that of the constant injection. But the increment of temperature at the each step is small because the initial temperature is different. Nevertheless the consumed heat energy for each step is even small than that of constant injection, the injected heat energies of both cases are same as listed in Table 1. As afore mentioned, the most of the injected heat is used for dissociating hydrates and heat loss to surroundings not for rising the temperature of core.

Table 1. The comparison of injected heat energy between constant and step-wise heat rate injection.

Electric Power (W)	Heat injection Method					
	Constant injection			Step-wise injection		
	Injected heat energy (kJ)	Temperature (K)		Injected heat energy [cumulative] (kJ)	Temperature (K)	
		initial	final		initial	final
4.3	16.09	274.55	275.46	15.76 [15.76]	274.55	275.46
8.8	40.24	274.55	276.31	31.28 [47.58]	275.46	276.16
13.4	51.78	274.55	277.05	57.19 [104.77]	276.16	276.91
17.7	86.45	274.55	277.81	53.08 [187.85]	276.91	277.52

Dissociating Experiment

In this study, dissociation experiments are performed to analyse the flowing behaviors of dissociated gas and water and production efficiencies at the hydrate gas reservoir by electric heating. The electric heating methods using this study are preheating and continuous heating: preheating for the improvement of initial productivity by dissociating hydrate adjacent outlet and continuous heating for increasing the mobility and accelerating the dissociation. Preheating method was injected with the heat energy of 8.8 W for 10, 20, 40 min. and then opened the outlet valve which the outlet pressure is set to 2.4 MPa. Continuous heating method was injected with the heat energy of 8.8 W and simultaneously opened the outlet valve. Also, the depressurization method without heat injecting is performed to investigate the effect of heat injection in detail. The pressure and resistance behaviors during the depressurization and heat injection are shown in Fig. 9 ~ Fig. 11. From these figures, the time of depressurization when coinciding with inlet and outlet pressure in Fig. 9 takes longer than those of heat injection in Fig. 10 and Fig. 11. Even if the high permeability core of 248.6 md is used, the inlet pressure is not appeared to be sensitive to outlet pressure change because of low absolute permeability where pores are plugged by hydrate. Hence, if the inlet and outlet pressure is almost same, hydrates are completely dissociated. From this result, heat injection method takes short time to dissociate than depressurization. Also, it is seen that the continuous heating method takes short time to dissociate than preheating. The inlet pressure of continuous heating is not suddenly decreased unlike the preheating and depressurization because of continuous injecting heat.

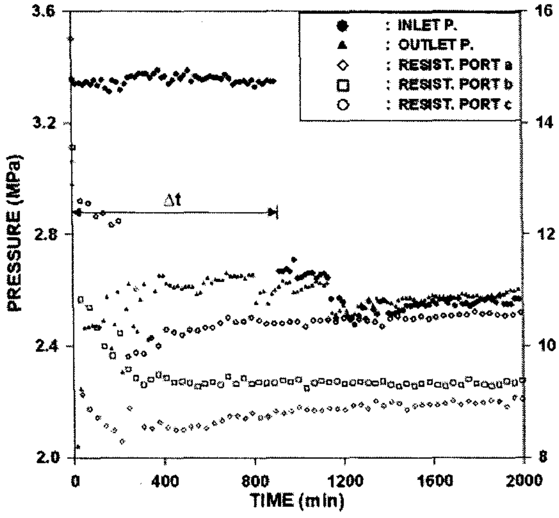


Fig. 9. Pressure and resistance behaviors during hydrate dissociation under only depressurization without heating.

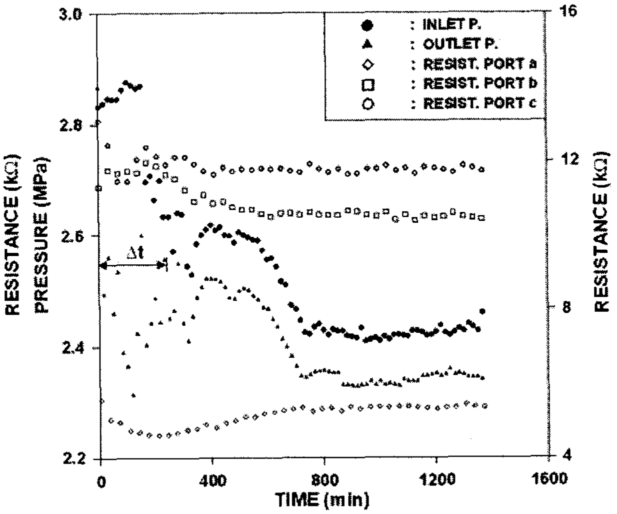


Fig. 10. Pressure and resistance behaviors during hydrate dissociation under continuous heating.

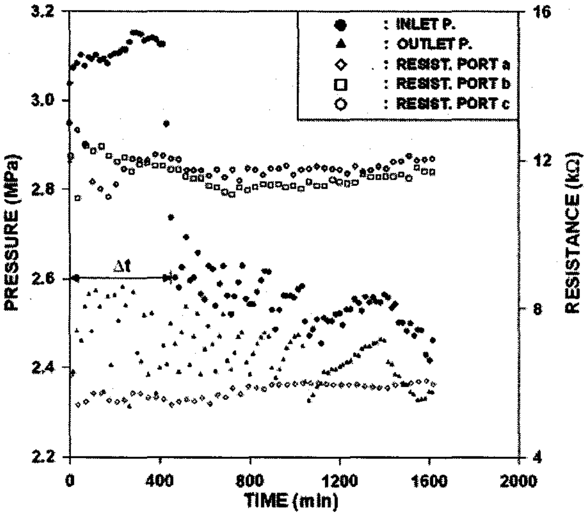


Fig. 11. Pressure and resistance behaviors during hydrate dissociation under preheating for 10 min.

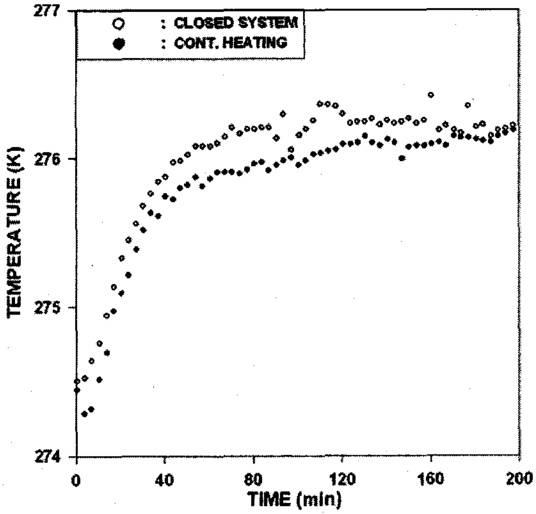
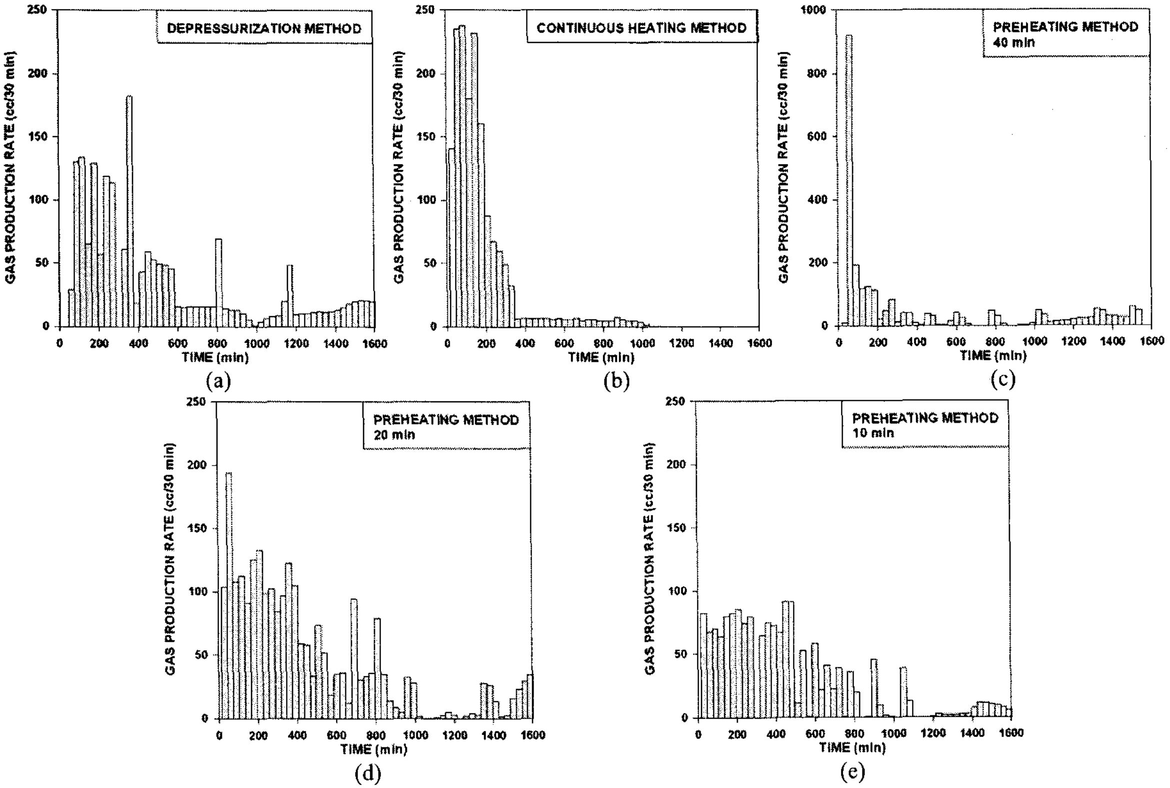


Fig. 12. The comparison of the core temperatures between the closed system and continuous heating system.

To investigate the behaviors of temperature between closed system and flowing system with constant heat injection, the average temperature of core is shown in Fig. 12. From this figure, the temperature of both cases are increased by injecting the heat and the temperature of flowing system is slowly increased and equal in comparison with that of closed system because of the heat loss from produced the gas and water. At the initial production period, it is noted that the temperature is decreased because the injected heat is used for dissociating the hydrate and the dissociated gas and water is produced together with heat. Also, the temperature of heat injection port in flowing system is 294.1 K at equilibrium whereas that of closed system is 297.1 K, so the difference between two is 3K. The difference is because the heat loss of produced gas and water is occurred in heat injection port, namely gas outlet.

To investigate the production behavior, the measured gas production rates by continuous heating, preheating, and depressurization experiment are shown in Fig. 13. From the investigation of gas production rate by depressurization in Fig. 13 (a), the gas dose not flow until 45 min because the pores are plugged by hydrate and as hydrate is dissociated, the dissociated gas are flowing due to increasing of the permeability. In the case of continuous heating as shown in Fig. 13 (b), the gas production rate for 200 min after production is larger than that of other methods because the gas is flowing at the start of production as the dissociation is accelerated by injected heat and the mobility of gas and the dissociation rate are improved by continuous heating. The measured gas production rates by performing the depressurization after preheating for 10, 20, 40 min are shown in Fig. 13(c) ~ Fig. 13(e). From these figures, as temperature is increased by preheating, hydrate is dissociated and dissociated gas is flowing at the start of production. Also, it is seen that the initial production rate is increased as the time of preheating is longer. Especially in case of preheating for 40 min in Fig. 13 (c), the initial gas production rate is about 4 ~ 9 times larger than that of preheating for 10 and 20 min and the gas production is almost ceased after producing for 200 min. It is similar case such as the flowing experiment in core with saturated gas because the hydrate is completely dissociated as temperature is increased by heat injection.

From the comparative study of cumulative gas production as shown in Fig. 14, the initial and cumulative gas production of preheating for 40 min is the largest than others. This is because the scale effect is appeared by performing experiment in small size of core and so the hydrate is completely dissociated as the temperature of a whole core is increased by heat injection. From the investigation of cumulative gas production by continuous heating, the initial productivity is large but the final cumulative gas production is small. Therefore, it is seen that the energy efficiency of continuous heating is low because the produced gas volume is small comparing with the injected heat energy. Hence, the injected heat energy by continuous heating is used for dissociating hydrate as well as increasing the temperature of core but much of energy is lost by surrounding of the core, so it makes low energy efficiency. Also, from the comparison between preheating for 20 min and 10 min, it is seen that the initial gas production rate is different with preheating time but the total cumulative gas production is similar. Only the initial productivity is different because the permeability is changed to the extent of dissociating in the outlet by the amount of injected heat prior to flowing experiment and then the gas flowing phenomena is dominated by the difference between inlet and outlet pressure.



(a) (b) (c)

(d) (e)

Fig. 13. Gas production rates under various heating method.

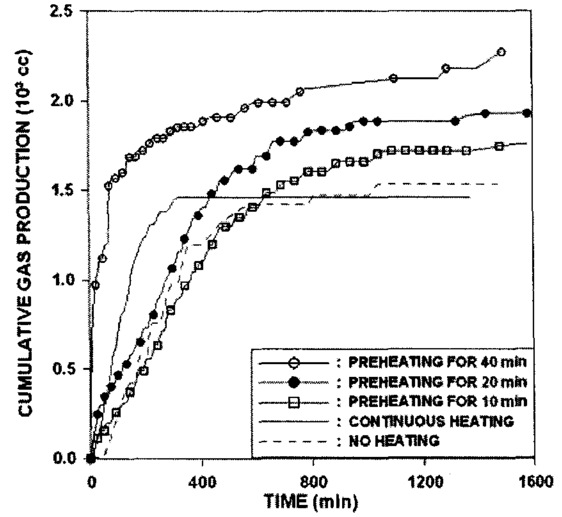


Fig. 14. Comparison of gas recoveries for different heating method.

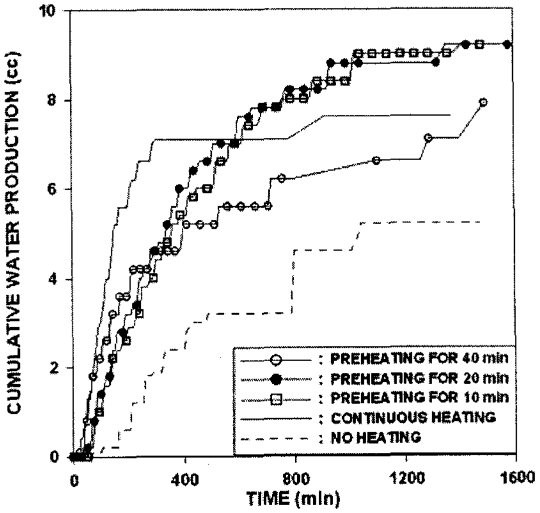


Fig. 15. Comparison of water recoveries for different heating method.

The cumulative water production is shown in Fig. 15. From this figure, it is seen that the initial water production of continuous heating is larger than those of preheating because the mobility is improved by decreasing the viscosity as the temperature is increased by continuous heating. From the comparison with the behaviors of water production for preheating, the initial water production of preheating for 40 min is large because the dissociated water is produced during the period of preheating.

4. Conclusions

In this study, the experimental apparatus has been designed and setup to analyze the dissociating phenomena of hydrate and production behaviors in porous rock using electric heating method. From the experimental results, the following conclusion is drawn:

1. From the investigation of the effect of injected heat energy on injection port, it is seen that the temperature of injection port is linearly increased as the injected heat energy is increased but the slope of the total injected heat energy is changed at 17.7 W. From the comparison with the enthalpy of dissociation and heat capacity of injection port and core, the injected heat energy until 17.7 W is more consumed by the dissociation of hydrate in porous rock than that of rising temperature to injection port and core.

2. From the temperature behaviors with injected heat energy, the temperature of core is large as the injection port is close and linearly increased as the injected heat energy is increased. But the increase of temperature of core is relatively small than that of injection port. This is because the only 7.5% of the injected heat energy is consumed for the rising temperature of core. Also, it is seen that the dissociation phenomena by electric heating is coincided with the hydrate equilibrium line.

3. From the experimental results between constant and step-wise heat injection, the temperature of injection port and core are the same, however the total injected heat energy is considerably different between the two methods. This is because the injected heat energies have more consumed for dissociating the hydrate and the heat loss of kerosene used by confining pressure than for increasing the temperature of core itself.

4. In the experiment of dissociation by electric heating method, the time of coinciding with inlet and outlet pressure, namely, the dissociating time takes shorter as the injected heat energy is increased. Therefore, the dissociation of hydrate is accelerated with heat. At the initial production period, it is noted that the temperature is decreased because the injected heat is used for dissociating the hydrate and the dissociated gas and water is produced together with heat.

5. From the investigation of gas producing behaviors for various heat injecting methods, as the injected heat is greater, dissociation is accelerated faster at outlet and hence the initial gas production becomes higher. Also, it is shown that the initial gas productivity under the constant heating method is better, however, the energy efficiency is low because of smaller amount of the produced gas comparing to the amount of heat injected. From the results of preheating method, it is seen that gas production only at the initial stage is different with the preheating time, but the producing behaviors of gas production are similar. This is because only the initial productivity is different with the extent of dissociating in the outlet by preheating and then the gas flowing phenomena is dominated by the pressure difference. It is seen that the initial water production of continuous heating is larger than those of preheating because the mobility is improved by decreasing the viscosity as the temperature is increased by continuous heating.

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