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Investigation of CO_2 hydrate formation conditions for determining the optimum CO_2 storage rate and energy: Modeling and experimental study

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A B S T R A C T

In this study, optimum conditions for CO_2 hydrate formation are investigated in order to determine the maximum CO_2 storage rate and optimum energy consumption. First, a wide range of new experiments are carried out by using three-blade, six-blade and anchor impellers. For each experiment, a mass transfer model and a semi-empirical equation are utilized and the amount of energy consumption is measured. Temperature, impeller speed, initial pressure and volume of water, surface tension and the diffusion coefficient of CO_2 are considered as the factors that affect the kinetics of CO_2 hydrate. Maximum energy savings is achieved with maximum hydrate formation rate. It is found that the impeller speed is the most effective factor here. Moreover, at a given impeller speed, the hydrate formation rate is four times greater than the three-blade impeller when a combination of six-blade and anchor impellers is used. In addition, the rate of hydrate formation becomes 2, 1.6 and 3 times greater by reducing the volume of water, increasing the temperature and initial pressure and increasing the concentration of surfactant up to its optimum concentration in such a way that the energy consumption reduces from 1.92 kWh to 0.08 kWh when these effective parameters are changed.

1. Introduction

The rapid growth of energy technology is putting pressure on the modern society to use large-scale energy sources, particularly conventional fossil fuels such as coal, oil and natural gas. On the other hand, fossil fuels have negative effects on climate due to increasing CO_2 in the atmosphere and global warming. Therefore, various methods have been considered to improve energy conversion and efficiency. Although utilizing renewable energies including solar, wind, hydropower and bioenergy or low carbon fuels such as natural gas, hydrogen and nuclear power could be a solution for this problem, the separation of CO_2 is a conventional approach to reduce CO_2 emissions. Different approaches exist that are applicable for isolating the CO_2 from the fuel gas stream. The wet scrubber, dry regenerable sorbents, membranes, cryogenics, pressure and temperature swing adsorption are the advanced approaches used for CO_2 separation. The high required dosage of chemicals, the recovery of the chemicals, the high amounts of energy consumption and the high pressure process are some of the limitations hindering the application of these separation techniques. There are a few reports in the literature that indicate that new technologies (such as membrane separation, cryogenic fractionation, and adsorption by molecular sieves) are even less energy-efficient than chemical absorption. Therefore, researchers have focused their efforts more on new technologies with low energy penalty [1–3].

The separation of CO_2 based on hydrate formation is an approach which has a low energy loss (6–8%) [1]. This method can be a suitable way of CO_2 separation for high pressure processes. In the last decade, the researchers have focused on the development of this method for CO_2 capture and storage. For example, Li et al. performed a study on the CO_2 capture process from the simulated fuel gas based on hydrate technology. They showed that the usage of TBAB (as an additive) can enhance the separation efficiency [4]. Also Surovtseva et al. designed a pilot plant for CO_2 capture and storage by the combined cryogenic and hydrate method [5]. On the other hand, a realistic evaluation of energy costs was done by Duc et al. [6]. Their results showed that the cost of energy was about 16.8–29.6 €/ton of captured CO_2. Their findings were informative due to a comparison with classical technologies such as membranes and amines (The energy cost was about 20–30 €/ton of captured CO_2). Yang et al. also

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Table 1
Materials applied in this investigation.

Component	Chemical formula	Purity	Supplier
Carbon dioxide	CO_2	99.9%	Technical Gas Services
SDS	$C_{12}H_{25}NaO_4S$	≥98%	Merck, Germany
Water	H_2O	deionized-distilled	Bahrezolal, Iran

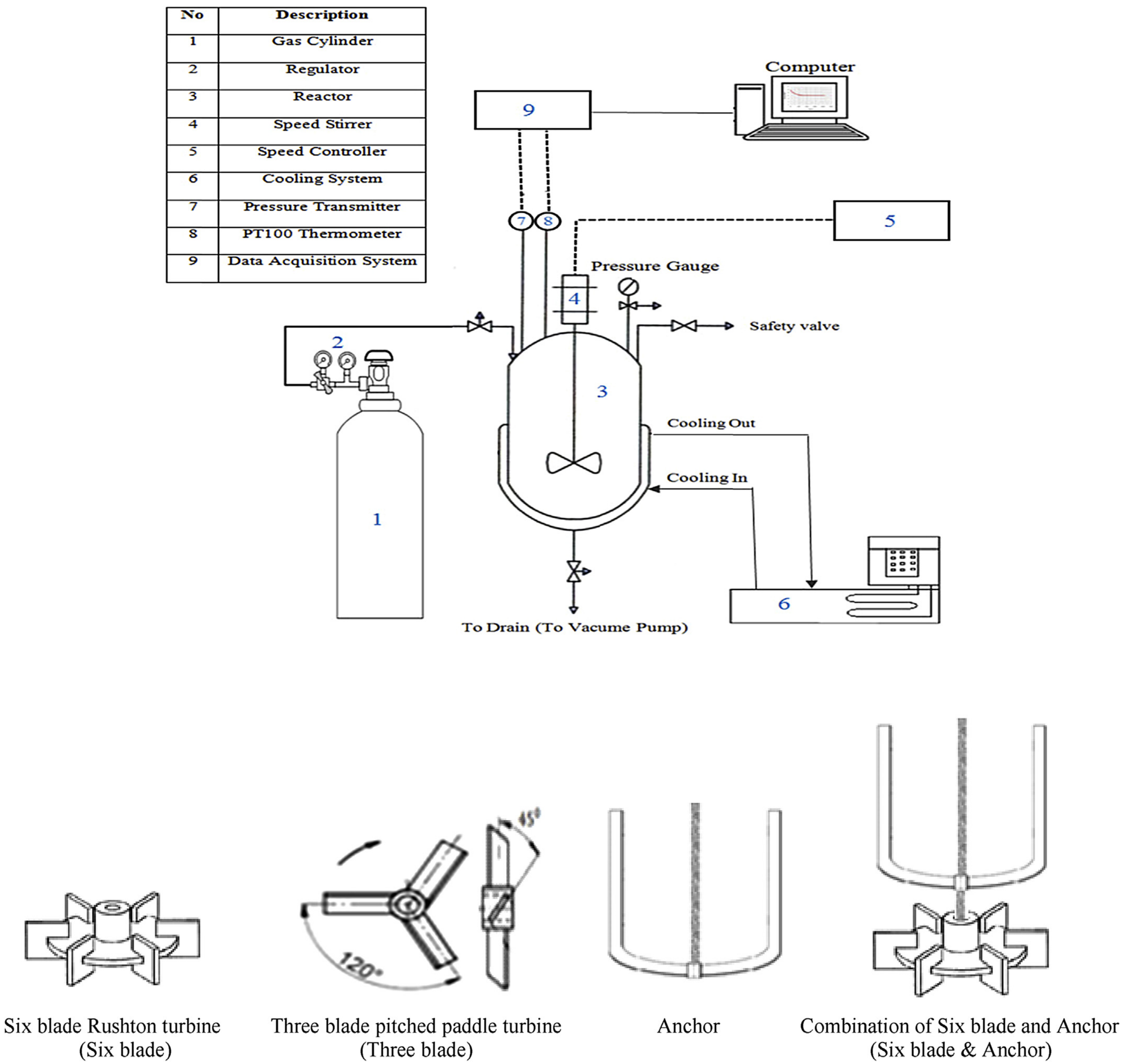

Fig. 1. Different parts of hydrate formation apparatus and its associated impellers.

studied the promotion effects of additives to achieve high storage rates and low energy consumption in HBGS (Hydrate-based gas separation) [7]. Linga et al. investigated the application of hydrate for CO_2 capture. They developed a reactor with gas-inducing impellers for enhancement of the rate of CO_2 storage [8]. Also in a few reports in the literature, fixed bed reactors are applied for energy saving in the CO_2 capture process by hydrate, although the rate of CO_2 storage may be low [9,10]. Furthermore, CO_2 hydrates can be applied for cool-energy storage and they can be used instead of methane for extraction of methane from the hydrate ocean sediments known as a future source of energy. Due to the mentioned advantages of the gas hydrate, the successful usage of hydrate mainly depends on the kinetics of hydrate formation, so realizing hydrate formation rate at different conditions is of importance [11–14].