Study of Thermal Supply Mode of Floating Nuclear Power Plant in Offshore Oil and Gas Fields

S F Zou¹,², D X Gong¹, J Song¹, J Zhao¹ and X H Zhang¹
¹Wuhan Second Ship Design and Research Institute, Wuhan 430064, China

E-mail: zsf9010@126.com

Abstract. The floating nuclear power plant (FNPP) is a solution to the thermal supply in offshore oil and gas fields, including the applications in thermal recovery and flow assurance. The output power of marine reactors under development in China matches the thermal demand of offshore oil fields. In order to analyse the thermal supply mode, the following aspects are investigated: the application scenarios, the thermal loss of the thermal supply pipeline, and the selection of platform type. Then, a case study is presented to illustrate the applicability of FNPP in the Bohai Sea for the enhancement of oil recovery. The case shows that the current solution works well with the offshore marginal oil field. The future solution is also discussed as to further improve the economy of FNPP.

1. Introduction

Thermal Energy is important and indispensable in petroleum and gas exploitation. The usage of thermal energy covers from the wellbore – the enhancement of recovery, to the pipeline – the flow assurance, and finally to the terminal equipment – the processing of oil and gas products.

For viscous oil, the recovery rate can be enhanced through the methods of steam huff and puff, and steam or water flooding. Both methods are based on the injection of thermal fluid; and the thermal fluid injected into an offshore wellbore is usually multi-component thermal fluid or thermal water/steam. Currently, the temperature of injected thermal fluids is up to 350 °C in offshore fields in China [1]; and the injection of supercritical water (> 22.1 MPa and 374 °C) has been investigated and tested in land oil fields [2].

Since the temperature at the sea bottom can sometimes approach the freezing point of water, the wax deposition (for oil field) and the formation of hydrates (for gas field) are likely to arise in the transportation pipeline. Both the wax precipitation temperature and the hydrates formation temperature depend on the component of oil or gas and the operating pressure. Normally, the wax deposition and the formation of hydrates could be inhibited at above 80 °C and above 20 °C, respectively.

Thermal energy is also in demand for the processing of oil and gas products on the offshore platform, including phase separation, dehydration of crude oil, and pre-heating of fuel oil and gas. The processing temperature is usually below 100 °C.

In an offshore oil or gas field, the source of heat power comes from the combustion of fossil fuels (natural gas, the associated gas, the processed fuel oil or diesel), as well as the electrical heating. Currently, the electricity on an offshore oil or gas platform is generated by gas turbine or diesel generator. With the exploitation going on, the production of oil and gas declines and becomes more unstable, which results in more unstable thermal and electricity supply. Besides, the air pollution caused by the combustion of fossil fuels is also inevitable. Nowadays, the comprehensive utilisation of
nuclear energy is encouraged by the National Development and Reform Commission of China and the Ministry of Science and Technology of China. The floating nuclear power plant (FNPP) is a promising solution to the energy and water supply in offshore oil and gas fields, as it combines electricity generation with thermal supply and water desalination. One of the oil giants in China, the CNOOC, even proposed an idea of nuclear-powered sub-sea workstation [3].

Nuclear power unit was once installed on merchant ships for propulsion [4]–[6]. Recently, the first FNPP for merchant use, the ‘Akademik Lomonosov’ built by Russia [7],8], has already started generating electricity. Most of the FNPPs under operation and development mainly target at electrical supply as well as building heating at remote coastal towns, islands and offshore platforms. According to the handbook of IAEA [8], the FNPPs currently under operation or development in the world are all based on pressurised water reactors (PWRs), as PWR is most mature among all the reactor types. For the FNPPs currently under development in China, two reactors are carried on a single platform. The thermal power supply of a single reactor ranges from 100 MW to 300 MW, and the output electrical power is 25–100 MW [8],[9]. The calculated electricity generation cost of a nuclear power plant is roughly the same with the current cost in offshore oil fields; and it will be further reduced after the FNPPs are mass constructed. For most of the FNPPs, the platform type is a floating vessel, although other types have also been proposed, such as a submersible capsule (FlexBlue, France [10],[11]) and a semi-submersible cylinder (OFNP, USA [12],[13]).

Although one or two marine reactors can also meet the demand for industrial heating in an offshore oil and gas field, the thermal supply mode is still undetermined. The thermal energy can be either conveyed by fluids or produced by electricity. If the thermal efficiency of fluid transportation is higher than the electricity generation in the secondary loop, the thermal supply pipeline is the better mode; otherwise, the electrical heating is the better mode.

Since the thermal loss of a thermal supply pipeline increases with its length, it is important to find the ‘critical’ length, below which the thermal loss of the pipeline is smaller than the electrical heating (i.e. a thermal supply pipeline is more ‘economic’). Moreover, as either or both of the supply platform and the receiving platform can be movable on the sea surface, the transporting temperature will be limited if there are flexible joints on the whole transporting passage. For this reason, it is also important to select a suitable platform type for the FNPP.

This work aims at the industrial heating of offshore oil and gas fields in China based on FNPP. First, a rough power demand is analysed in order to illustrate the applicability of the FNPPs currently under design in China. Then, the thermal loss along the thermal supply pipeline is calculated so as to find the ‘economic’ length. Later, the selection of platform type is also investigated. Finally, a case study is performed based on the results. Future solution is also discussed.

2. Power demand analysis
Before the thermal supply mode can be discussed, the output power of the FNPP should match the demand first. This section mainly focuses on the power demands for the thermal recovery of viscous oil (i.e. thermal injection) and the flow assurance (i.e. thermal preservation of pipeline).

2.1. Thermal recovery of viscous oil
The recovery of viscous oil can be enhanced by the injection of thermal fluids. Steam or hot water can be generated on the FNPP. According to the current field condition, the pressure and temperature of steam injected into a wellbore can reach 16 MPa and 350 °C for huff and puff, and the injection rate is about 10 t/h [1]. Assuming that the feed water is at atmospheric pressure and 20 °C; then, it can be figured out that the demand of thermal power is 7.036 MW according to the enthalpy. Apparently, the electricity power generated by a single floating nuclear reactor can meet the demand, not to mention the direct use of nuclear thermal power. Theoretically, the injection condition could be raised to the supercritical state within the power capacity of one reactor, though electrical heating is unavoidable. An offshore oil platform usually collects products from several or a dozen wellbores. For each wellbore, the injection of steam usually lasts for 7–20 d, followed by a few weeks of soak time and
several months of production before the next injection. Thus, the thermal production on the FNPP can still be continuous, since the thermal fluid is injected into the wellbores alternately.

As for hot water flooding, the temperature of injection can be lowered to 200 °C, which perfectly meets the temperature of the secondary loop. For the injection rate of 10 t/h, the demand of thermal power is 2.152 MW.

For steam huff and puff, the wellbore for injection and that for production is the same; while for hot water flooding, the thermal fluid is injected into one wellbore and the products flow out of other wellbores.

2.2. Flow assurance
According to the rules issued by China Classification Society (CCS), the temperature of the pipeline should be at least 5 °C above the temperature of wax deposition and hydrates formation [14]. Assuming that the coating of the pipeline consists of a thermal insulating layer and a concrete layer; and then, the thermal loss can be roughly estimated from the following input conditions:
- Pipe structure and thermal properties: ‘Pipeline A’ in Figure 1;
- Temperature of sea water at infinity: 0 °C;
- Temperature of seabed at infinity: 0 °C;
- Temperature at the inner surface of the thermal insulating layer: 85 °C.

The theoretical maximum limit of the thermal loss appears at the condition where the temperature of the outer surface is same with that at infinity (i.e. 0 °C). Then, it is not difficult to estimate from the Fourier’s law that the thermal loss should be 0.346 MW/km at most, no matter the pipeline is buried or not. According to the rules issued by CCS, electrical heating is the recommended tracing method. Theoretically, a reactor with the electricity power of 25 MW could afford the thermal power for the flow assurance of a pipeline network with a total length of at least 72 km (neglecting the loss in the circuit).

3. Thermal supply modes
For the flow assurance, the thermal supply mode is electrical heating. For the thermal recovery, however, the thermal supply mode can be thermal fluid (water or steam), electrical heating, and hybrid mode, depending mostly on the thermal loss of the thermal supply pipeline as well as the type of both the FNPP and the receiving platform.

3.1. Thermal loss
The necessity of a thermal supply pipeline is decided by the thermal loss of the pipeline itself. The electricity generating efficiency of the FNPPs under development in China is about 25%. In other words, a thermal supply pipeline is uneconomic if the thermal loss along the pipeline exceeds 75%. Obviously, the thermal loss increases with the length of the pipeline; besides, the thermal loss is also related to the diameter and the wall thickness of the pipeline, as well as the fluid temperature.

The thermal loss is defined as below:

\[
q_{\text{loss}} = h_{\text{outlet}} - h_{\text{feed}} - h_{\text{inlet}} - h_{\text{feed}}
\]

where \( h \) is the enthalpy of thermal water. The ambient temperature is taken as the temperature of the feed water.

The heat transfer between the fluid in the pipeline and the seabed is calculated based on the assumption that the pipeline is buried, and the temperature of seabed at infinity is 0 °C. The thermal water is supplied at the rate of 10 t/h; and the inlet temperature is set to 5 MPa in order to avoid two-phase flow (which will cause slugging problem in an offshore pipeline-riser system). The calculation procedure is like the case of a wellbore [15]; the thermal loss of the downcomer and the riser can be neglected [16]. Two pipelines with different diameter and wall thickness (see also Figure 1) are calculated. The inner diameter of Pipeline B is half that of Pipeline A. The outlet temperature and the
total thermal loss versus the length of the pipeline after 10 days of thermal water supply are presented in Figures 2 and 3.

![Diagram of pipeline dimensions and thermal properties.](image)

**Figure 1.** Pipeline dimensions and thermal properties.

Figure 2 shows that the outlet temperature decreases with the pipeline length, but with a slower trend. Correspondingly, the thermal loss increases with the pipeline length, and also with a slower trend, as displayed in Figure 3. These results can be explained by smaller temperature difference between the thermal water and the seabed with the distance goes on. For a marine PWR, the temperature of the secondary loop (i.e. the inlet temperature) is usually under 250 °C. If the injection temperature is above the outlet temperature, or steam is needed, the electrical heating on the wellhead platform is inevitable.

![Graphs showing outlet temperature versus pipeline length.](image)

**Figure 2.** Outlet temperature versus pipeline length.

By comparing the two subplots in Figure 3, and also the two subplots in Figure 2, it is evident that the thermal loss of Pipeline B is smaller than that of Pipeline A. As is shown in Figure 1, the thickness of the insulating layer and the concrete layer are the same for the two pipelines; and the thickness of steel pipe is even smaller for Pipeline B. Then, it can be concluded that the thermal loss is smaller for a pipeline with smaller inner diameter on condition that the thickness of all the pipe layers are the same. Although Pipeline B has a smaller inner diameter, the frictional pressure drop is still as small as several kPa/km, which can be neglected since the absolute pressure is about 5 MPa. Therefore, the diameter of the thermal water pipeline should be properly reduced. All the trend curves in Figure 3 are lower than 0.75, indicating that the transportation of thermal water is more economic than electrical.
heating. The length that corresponds to $q_{\text{loss}} = 0.75$ is also calculated for the two pipelines, respectively. For Pipeline A, the ‘economic’ length is within 11.8 km; while for Pipeline B, the ‘economic’ length is no more than 17.7 km.

![Outlet temperature versus pipeline length](image)

**Figure 3.** Outlet temperature versus pipeline length.

Although the thermal supply is more economic if the distance between the FNPP and the receiving platform is shorter, there are still circumstances that several receiving platforms share the thermal supply from one FNPP. Take the condition of two receiving platforms as an example. It is apparent that the FNPP should be as close to one receiving platform as possible on condition that other things being equal, because Figure 3 shows that the thermal loss is a concave function of the pipeline length.

3.2. **Type of Platforms**

The thermal supply mode also depends on the type of both platforms. If either platform has a freedom in the horizontal plane (i.e. at the sea level), the thermal supply pipe (or part of it) must be flexible. However, the swivel joint on a single point mooring terminal is unable to withstand the temperature higher than 120 °C, which limits the supply temperature of the thermal fluid and increase the electricity consumption.

The type of offshore platform in China covers jacket platform, bottom-supported platform, gravity platform, jack-up platform, FPSO and semi-submersible platform. As the FNPP for thermal supply must be movable, the jacket platform and the gravity platform are unsuitable. According to the chart of the Bohai Sea, the average depth is 30 m. Therefore, the bottom-supported platform is unlikely to be adopted. On the contrary, the semi-submersible platform is overqualified. Hence, the recommend types of FNPP are the jack-up platform and the FPSO (or a floating vessel). Concerning that the legs of a jack-up platform can be fixed on the seabed under operation conditions, a flexible connection between the FNPP and the wellhead platform will be avoided if the nuclear power plant is loaded on a jack-up platform [17]. In that case, it becomes possible to raise the temperature of the thermal fluid and reduce the electricity consumption.

4. **Current solution – a case study**

In this section, the conceptual solution of thermal supply based on the current state of the art in the FNPP is presented by a case study. A group of offshore oil fields in the Bohai Sea, LD 27-2/LD 32-2, is taken as an example.

4.1. **Basic information**

LD 27-2 and LD 32-2 are marginal oil fields in the east part of the Bohai Sea. LD 27-2 has one wellhead platform, the WHPB; and LD 32-2 consists of one wellhead platform, the WHPA, and one production and storage platform, the PSP [18]. The relative locations of the platforms are displayed in
Figure 4 according to Reference [18]. The average depth of the waters around the fields is 27 m; and the nearest oil field is 70 km away. The electrical power station is on the PSP, with a total installed capacity of 24.82 MW (this figure is calculated according to the network resource [19]).

WHPA and WHPB platforms collect the products from 18 and 16 wellbores, respectively [20]; among those 12 wellbores connected to WHPB platform require thermal recovery [1]. A miniature modular steam generator has been installed on the WHPB platform for the supply of saturated steam at a maximum rate of 11.2 t/h. The maximum operating pressure and temperature is 21 MPa and 350 °C [1]. The fuel for the steam generator is the processed crude oil.

4.2. Thermal supply mode
At present, there is no special regulation for the restricted planning area of a marine reactor; and the safety distance between two platforms is not mentioned in the related regulations, either. The restricted planning area of a land-based nuclear plant is usually within 5 km around the reactor; while the nuclear emergency zone for FNPP is within 500 m radius of the reactor, according to the calculation [21]. For self-propelled ships, the routes are usually 3–4 km away from platforms [22]. Based on the above information, the distance between the FNPP and any oil platform should be at least 5 km for conservative reasons. Subsequently, the suggested location of the FNPP is 5 km away from WHPB platform and 8 km away from WHPA platform (see also Figure 4). The minimum distance between the FNPP and the connecting line between the two wellhead platforms is above 2 km.

Since the distance between the FNPP and WHPB platform is 5 km, and the injection temperature is above 250 °C, the thermal supply mode is the combination of thermal water and electrical heating. The scheduled period of thermal supply is 6 month per cycle. Since the total number of thermal recovery wellbore is 12, the injection for each wellbore lasts about 15 days.

4.3. General design
The FNPP is a jack-up platform, on which two PWRs are loaded. The containment vessel is beneath the sea level. The thermal water is first transported to an unattended relay platform (see also Figure 4) before it arrives the wellhead platforms. The current electricity capacity (24.82 MW) can be replaced by one reactor (100 MW_thermal/25 MW_electric); and the other reactor is for thermal recovery (combined heat and electricity generation). Although the thermal recovery is currently implemented on WHPB platform, the future implementation on WHPA platform should also be considered. The main parameters (listed in Table 1) can be preliminarily determined by reference to the monograph [9].

| Parameter                              | Value        | Parameter                              | Value       |
|----------------------------------------|--------------|----------------------------------------|-------------|
| Nuclear power                          | 100 MW       | Thermal water – inlet temperature      | 200 °C      |
| Total electrical power capacity        | 20 MW        | Thermal water – pressure               | 4 MPa       |
| Maximum electrical power for           | 18 MW        | Thermal water – maximum flow rate      | 20 t/h      |
| thermal recovery                        |              |                                        |             |
| Secondary loop – pressure              | 4 MPa        | Maximum injection temperature          | 500 °C      |
| Secondary loop – temperature           | 250 °C       | Maximum injection pressure             | 25 MPa      |

Table 1 demonstrates that a marine reactor is suitable for the thermal supply to an offshore oil field, despite that the economy of the reactor can still be optimised by modification of the primary loop and the secondary loop.

5. Future solution – discussion
The future solution of thermal supply by FNPPs requires higher temperature and lower thermal loss. According to Figures 2 and 3, the thermal loss varies little with the injection temperature; and the outlet temperature of the thermal supply pipeline increases with the inlet temperature. Therefore, some types of fourth generation reactors would become the potential solution, such as the high temperature gas cooled reactor (HGTR), the lead-based fast reactor (LBR) and the Thorium-based molten salt
reactor (TMSR). The temperature of the secondary loop will be raised significantly compared with the secondary loop of PWR. Not only the inlet temperature will be raised, the efficiency of electricity generation will also be improved significantly. Hence, the application of the fourth generation reactors on FNPP is much more ‘economic’ than the current application of PWR. Among the reactor types mentioned above, the LBR had already been marinised by the former USSR.

As for the FNPPs based on PWR, the thermal loss of the thermal supply pipeline can still be reduced if its length can be reduced. This will become possible if the off-site emergency plan can be lifted owing to the improvement of inherent safety. The improvement of inherent safety depends on the further development of passive safety system and higher-level integration of marine PWR. In addition, a submersible platform for the nuclear power plant also helps to reduce the distance of thermal fluid transportation.

![Figure 4. LD 27-2/32-2 oil fields (platform models from network resources).](image)

6. Concluding remark
The thermal supply by a floating nuclear power plant is promising in offshore oil and gas fields, especially oil fields. The output power of a floating nuclear power plant can meet the demand of a wellhead platform; and a nuclear power plant will significantly reduce the emission of greenhouse gases and harmful gases compared with the combustion of fossil fuels. In this work, the thermal supply mode is studied, and the following conclusions are drawn.

(1) The thermal supply mode depends mostly on the thermal loss besides the temperature of the thermal fluid for injection; and the temperature for thermal fluid transportation may be limited by the type of platforms. A jack-up platform can help to raise the transportation temperature, and thus improve the economy of FNPP.

(2) A pipeline with smaller inner diameter can reduce the thermal loss on condition that the thickness of each layer is the same. The thermal loss increases with the pipeline length, but with a slower trend. These results can help to optimise the pipeline design and the site selection of the FNPP.

(3) For the safety reasons, the distance between the FNPP and the wellhead platform is quite large at present. However, with the development of unattended wellhead platforms, the distance would be possibly nearer, which could help to further reduce the thermal loss.

(4) The future solution depends on the application of the fourth generation reactors and higher inherent safety of marine reactors.

Acknowledgments
This work is supported by China National Energy Administration (grant No. NY20150201) and Science and Technology Department of Hubei Province (grant No. 2019CFB280).

References
[1] Li P, Liu Z, Zou J, Liu H, Yu J and Fan Y 2016 Injection and production project of pilot test on steam huff-puff in oilfield LD 27-2, Bohai Sea Acta Petrol. Sinica 37 242–47
[2] Zhao Q, Guo L, Huang Z, Chen L, Jin H and Wang Y 2018 Experimental investigation on enhanced oil recovery of extra heavy oil by supercritical water flooding Energ. Fuels 32 1685–92
[3] Zeng H, Li Q and Wu Y 2006 The technology of sub-sea workstation for exploiting deep water resources Shipbuild. Chin. 47 1000-4882(2006)S-0001-08
[4] Koehler E W 2006 Nuclear Ship Savannah (Washington D.C.: U.S. Maritime Administration)
[5] Rogan P, Lengar I, Snoj L and Ravnik M 2008 Evaluation of benchmark experiments of the otto-hahn nuclear ship – several configurations Proc. Int. Conf. Nucl. Energ. for New Europe 2008 (Ljubljana: Nuclear Society of Slovenia) 222
[6] Ali M F 2013 A Book: Nuclear Energy – Peaceful Ways to Serve Humanity (Web publisher: https://mirfali.com/) Chapter 10
[7] Kostin V I, Panov Y K, Polunichev V I and Shamanin I E 2007 Floating power platform at sea in nuclear emergency<br>Available at: https://www.doc88.com/p-385623169089.html
[8] Anonymous 2012 A brief discussion on substation automation system Available at: https://www.doc88.com/p-385623169089.html