



DESIGN OF THE STEAM REFORMER FOR THE HTR-10 HIGH TEMPERATURE PROCESS HEAT APPLICATION

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Abstract

The 10MW High Temperature Reactor Test Module (HTR-10) is being constructed now. It plans to be operated in 2000. One of its objectives is to develop the high temperature process heat application. The methane steam reformer is one of the key-facilities for the nuclear process heat application system. The paper describes the conceptual design of the HTR-10 Steam Reformer with He heating, and the design optimization computer code. It can be used to perform sensitivity analysis for parameters, and to improve the design. Principal parameters and construction features of the HTR-10 reformer heated by He are introduced.

1. Introduction

The High temperature gas cooled reactor HTR-10 now is being constructed in the Institute Nuclear Energy Technology of Tsinghua University. It plans to be operated in 2000. Than some inherent safety experiments will be performed in the following 2 years. After these experiments the operating temperature will be increased to 900°C (or 950 °C). At the beginning of the 21 century, about 2 to 3 years will be used to install a nuclear process heat application system.

The methane-steam reformer heated by He (or N₂) is one of the key-facilities for the nuclear process heat application system. Generally speaking, the nuclear heating reformer is a tube-shell type reformer. In comparison with a fossil fuel reformer its heat transfer efficiency is lower, reforming transform ratio is smaller and price is higher. So in order to make it commercial competitive, it is necessary to optimize the design to increase the

productivity and decrease the cost of the reformer.

REFORM computer code is a design optimization computer code for the HTR-10 steam-methane reformer heated by He or N₂. It can be used to perform sensitivity analysis for different parameters, and to improve the design.

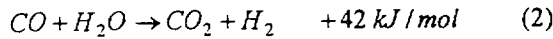
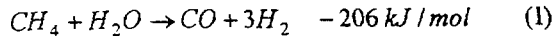
Principal parameters and construction features of the HTR-10 reformer by He (or N₂) are introduced.

2. Principal considerations for the reformer design

In Comparison with a fossil fuel reformer, the high temperature nuclear heat reformer has a series of disadvantages. For example: The forced convection heat transfer used in the nuclear heat reformer is less efficient than the radiation heat transfer used in a ordinary reformer, so the reforming temperature is lower about 50-100 °C than in ordinary reformer. From safety consideration the pressure of the

high temperature process heat application system must be higher than the pressure of the intermediate heat exchanger (IHX) secondary side.

As is known to all, according to the dynamical balance there are two principal reactions for the reforming process:



Increase of pressure or decrease of temperature results in decrease of H_2 productivity.

In order to increase the H_2 productivity following design considerations are adopted:

- To decrease the work pressure of the catalytic bed, To make $P_p \approx P_{He}$ (or P_{N_2})
- To increase the H_2O/CH_4 ratio in the raw gas low as possible.
- To preheat the process gas by residual heat of the production gas, to increase the process gas temperature at the inlet of the catalytic bed.
- To intensify heat transfer at out side of the catalytic bed.
- To increase the temperature difference between the H_2 (or N_2) and process gas.
- To improve heat transfer features of the fixed catalytic bed.

2.1 To decrease work pressure of the catalytic bed

Decrease of the reaction pressure can increase the transformation ratio of the CH_4 . From view point of safety, it requires that the He (or N_2) can't be leaked into the process gas when the catalytic tube is broken. So the pressure of the process gas should be higher than gas pressure in the IHX secondary side. For HTR-10 the gas pressure in the IHX secondary side is 3.2MPa. So the process gas

pressure at the outlet of catalytic bed is selected 3.4MPa. The pressure drop in the catalytic bed is about 0.6-0.8MPa. So the work pressure of the reformer should be selected about 4.0MPa.

The counter flow mode is adopted in the IHX for the He (or N_2) and the process gas. The pressure difference between the two gases at the inlet of the catalytic bed is about 0.8-1MPa, and at the outlet of the catalytic bed—only 0.2MPa, so that the pressure difference between the two gases can be kept minimum at the hottest pipe section.

2.2 To increase the H_2O/CH_4 ratio

In the transform process of the CH_4 , existed at the same time the carbon separation effect:

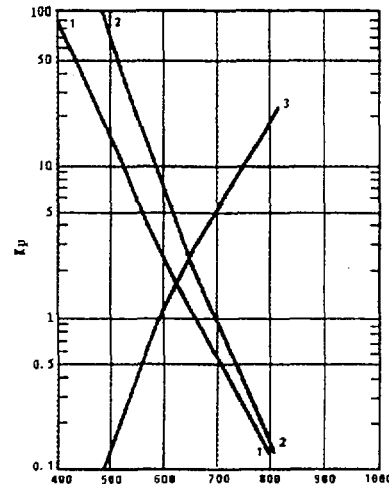
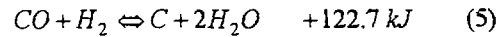


Fig.1 The balance constants of the reaction (3)~(5)

$$1: CO + H_2 = C + H_2O \quad K_p = \frac{P_{H_2O}}{P_{CO} \cdot P_{H_2}}$$

$$2: 2CO = C + CO_2 \quad K_p = \frac{P_{CO_2}}{P_{CO}^2}$$

$$3: CH_4 = C + 2H_2 \quad K_p = \frac{P_{H_2}^2}{P_{CH_4}}$$

The balance constants of the equation (3)-(5) and their dependence on temperature are given in the Fig.1. For different reaction the effects of temperature and pressure on the carbon separation are different. In order to avoid carbon separation in the above three reactions proper steam quantity should be selected.

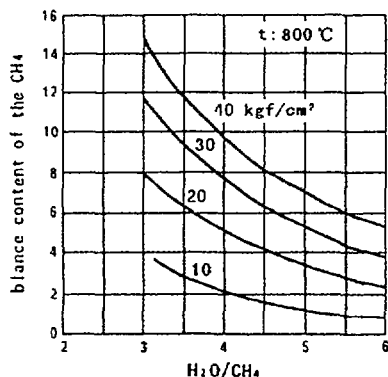


Fig.2 The effect of H₂O/CH₄ ratio on balance content of the CH₄

The effect of H₂O/CH₄ ratio on the balance content of the CH₄ in the CH₄-steam transform process is given in Fig.2. From Fig.2 it can be seen that increase H₂O/CH₄ ratio is to the benefit of transform reaction. But too big H₂O/CH₄ ratio results decrease of capability of the apparatus and increase of energy consumption. So the proper H₂O/CH₄ ratio should be selected.

2.3 To increase the CH₄-steam reforming temperature

Reforming reaction (1) is a strong endothermic reactor. Increase of the temperature is of benefit to increase of H₂ productivity.

If the He temperature at the outlet of the reactor core is increased to 950 °C, IHX secondary side outlet temperature is increased to 905 °C, the He (or N₂) temperature at the outlet and inlet of the reformer can be increased to 600/890 °C. Both the increase of reforming

temperature and the temperature difference between two side gases can improve the productivity.

Series connection operating mode for steam reformer (SR) and steam generator (SG) can increase the He (or N₂) temperatures at inlet and outlet of reformer. Consequently, it can also increase the temperature difference between the He (or N₂) and the process gas, and increase the productivity per unit power.

2.4 To intensify heat transfer on the He (or N₂) side

Construction of the tube-shell type reformer requires the forced convection mode on outside of the heat transfer tube. Efficiency of forced convection heat transfer for gas is lower than that of radiation heat transfer. In order to increase heat transfer efficiency it is necessary to increase velocity and turbulence of the gas flow.

Analysis shows that use of cross flow can improve heat transfer more than concentric pipe. But at the same time, the hydraulic resistance will be more.

Application of ribbed construction on the outside surface of the catalytic pipe can effectively increase the gas heat transfer coefficient. In our case, the total heat transfer coefficient can be increased to about 30%.

2.5 To improve the heat transfer features of the catalytic pipes

Dynamics analysis of the CH₄-steam transform shows that, existing catalyst, relatively high reaction velocity can be achieved under temperature 600-800 °C. In this case reforming reaction is controlled mainly by heat transfer and balance dynamics.

Use of increasing balance transformation rate and to intensify heat transfer outside catalytic pipes to increase transformation rate have been analyzed above. Analysis of heat transfer features shows the thermal resistance of

the catalytic bed cannot be neglected. So improvement of catalytic bed heat transfer features can also considerably increase transformation rate.

Heat transfer process in the catalytic bed is very complicated. It includes conventional heat transfer between solid particles and gases, heat conductivity in the solid particles and gases, and radiation heat transfer in the catalytic bed. All these processes effect on the final results of heat transfer. Therefore, usually empirical formulas are used for catalytic bed heat transfer calculation. In our design effective conductivity of the catalytic bed is used to character its heat transfer features:

$$\frac{\lambda_e}{\lambda} = \frac{\lambda_e^0}{\lambda} + (\alpha\beta) \text{Re Pr}$$

There

λ is gas heat conductivity

λ_e is solid particle heat effective heat conductivity

λ_e^0 is catalytic bed heat conductivity when the gas velocity=0;

α is ratio of sectional mass transfer velocity to the mass transfer velocity in the flow direction;

β is coefficient characteristic effects of particle diameters and distances between particles.

The effective heat conductivity of the catalytic bed depends on empty bed velocity, porosity of the bed, construction of the catalyst etc. Increase of the empty bed velocity can effectively improve heat transfer of the catalytic bed. But this means to increase the production intensity.

As mentioned above, catalytic bed heat transfer is a complicated process. Necessary experiments and verification are required.

3. Computer Code REFORM

Methane-steam reformer is a counter-flow mode, tube-shell type, gas-solid fixed-bed reaction-heat exchanger. In the reformer heating

gas is coming from the secondary side of the Intermediate Heat-exchanger (IHX). Main reactions occurred in the reformer are the equations (1) and (2). The computer code REFORM is used for reformer design calculation and parameter selection.

3.1 Main equations of the fixed-bed reaction apparatus

- The mass conservation equation:

$$Fdx=r_1dw \quad Fdy=r_2dw$$

There

F is entering rate of the raw gas, kmol/s;

x is methane transformation rate;

y is CO₂ formation rate;

w is weight of the catalyst, kg;

r₁ is reaction rate of the equation (1);

r₂ is reaction rate of the equation (2).

- The energy conservation equation:

$$\sum m_i C_{pi} dT = u_1 A_1 (T_{s1} - T) dZ + u_2 A_2 (T_{s2} - T) dZ - Fdx\Delta H_1 - Fdy\Delta H_2$$

There

ΔH_1 and ΔH_2 is reaction heat of the reactions (1) and (2), respectively;

m_i is mass of the i component, kmol/s;

C_{pi} is specific heat (at constant pressure) of the i component kJ/kmol · K;

T is process gas temperature in the catalytic tubes, K;

T_{s1} , T_{s2} is heating gas temperatures, K;

u is heat transfer coefficient, kJ/m²·s·K;

A_1 , A_2 is heat transfer area per length of the tube, m²/m;

Z is length of the tube (beginning at the inlet), m.

- The momentum conservation equation

$$dp = f' \left(\frac{\rho u^2}{d_s} \right) \left(\frac{1 - \epsilon_B}{\epsilon_B} \right) dZ$$

There

ϵ_B is porosity of the catalytic bed;

ρ is density of the fluid;

u is average empty bed velocity;

d_s is equivalent diameter of the particle.

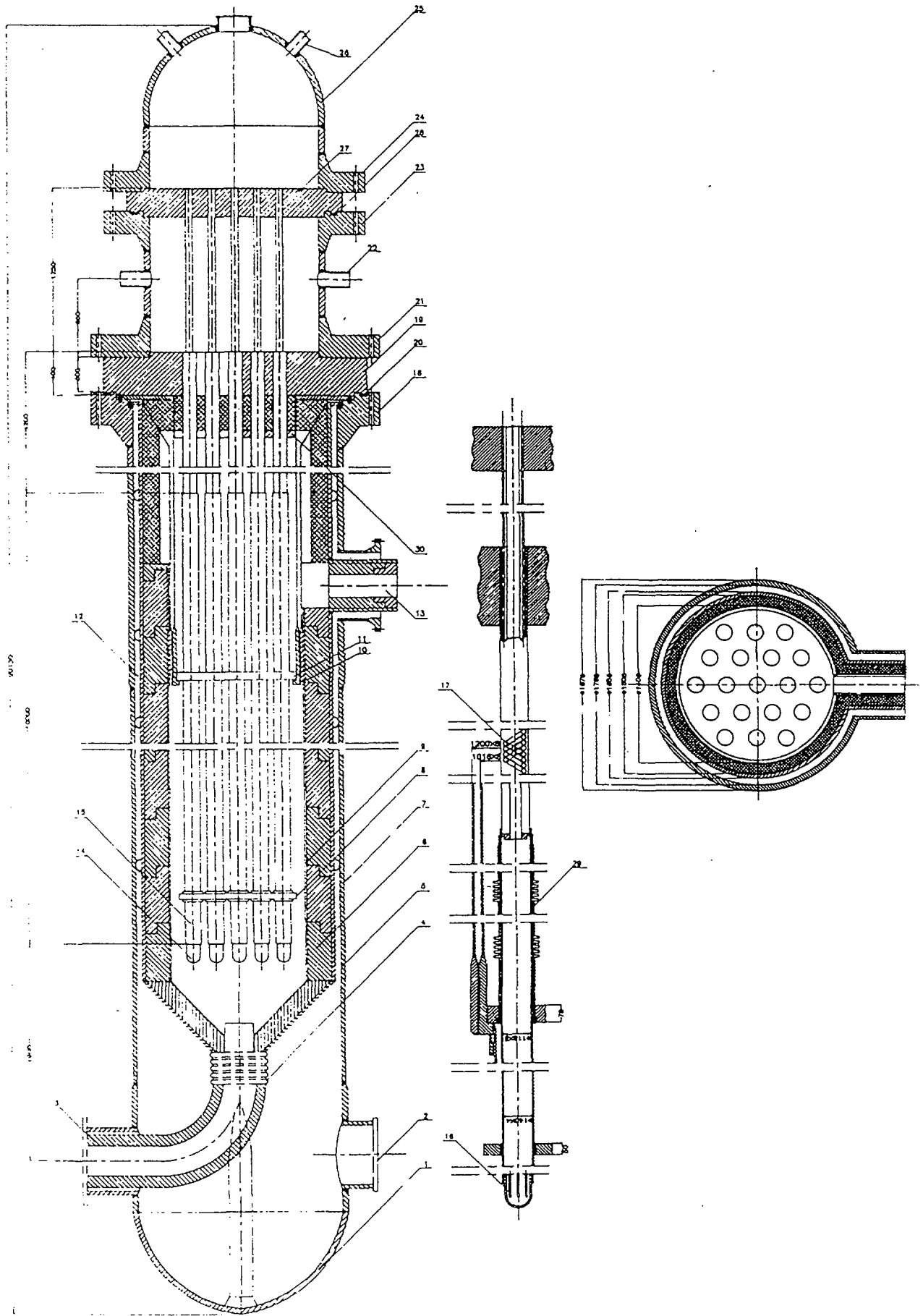


Fig.4 The construction of the reformer

4.1 Main parameters

Power of the reformer	3.09MW
Work pressure of the helium	3.0MPa
He flow rate	5.73T/hr.
He temperature at the outlet/inlet	600/890 °C
Composition of the process gas	
Raw gas	CH ₄ /H ₂ O=1:4
Product gas	CH ₄ : 3.11% CO: 6.32% CO ₂ : 5.74% H ₂ : 42.89% H ₂ O: 41.93%
Process gas flow rate	1.57 kg/s
Process gas temperature at the outlet/inlet of the catalytic bed	840/500 °C
Process gas pressure at the outlet/ inlet of the catalytic bed	3.7/3.4MPa

4.2 Construction parameters of the reformer

Parameters of the tube-bundle	
Number of the reformer tube	30
Diameter of the tube bundle	1400mm
Diameter of the catalytic tube	Φ 116×8mm
Active section length of the catalytic tube	10140mm
Diameter of the helium coat tube	Φ 140×4
Diameter of the centre guide tube	3× Φ 18×1.5
Parameters of the vessel	
Working pressure	4.4MPa
Working temperature	350 °C
Outside diameter, mm	2276 mm
Height, mm	20010mm
Parameters of the regenerator	
Working pressure	4.4 MPa
Outlet/inlet temperature	
Raw gas	320/500 °C
Product gas	600/400 °C
Diameter of the spiral tube	Φ 18×1.5
Number of the tubes	3×30
Outside diameter of the helical tube	Φ 54
Height	3.72m

4.3 Construction figures

The construction of the reformer is shown in Fig.4.