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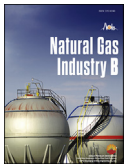
Natural Gas Industry B 3 (2016) 90–98



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Research article

Standardized surface engineering design of shale gas reservoirs

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Received 19 November 2015; accepted 1 February 2016
Available online 1 July 2016

Abstract

Due to the special physical properties of shale gas reservoirs, it is necessary to adopt unconventional and standardized technologies for its surface engineering construction. In addition, the surface engineering design of shale gas reservoirs in China faces many difficulties, such as high uncertainty of the gathering and transportation scale, poor adaptability of pipe network and station layout, difficult matching of the process equipments, and boosting production at the late stage. In view of these problems, the surface engineering construction of shale gas reservoirs should follow the principles of "standardized design, modularized construction and skid mounted equipment". In this paper, standardized surface engineering design technologies for shale gas reservoirs were developed with the "standardized well station layout, universal process, modular function zoning, skid mounted equipment selection, intensive site design, digitized production management" as the core, after literature analysis and technology exploration were carried out. Then its application background and surface technology route were discussed with a typical shale gas field in Sichuan–Chongqing area as an example. Its surface gathering system was designed in a standardized way, including standardized process, the modularized gathering and transportation station, serialized dehydration unit and intensive layout, and remarkable effects were achieved. A flexible, practical and reliable ground production system was built, and a series of standardized technology and modularized design were completed, including cluster well platform, set station, supporting projects. In this way, a system applicable to domestic shale gas surface engineering construction is developed.

Keywords: Shale gas; Unconventional; Surface engineering; Gathering system; Surface technology; Standardized design; Cluster wells; Integration

Shale gas refers to the natural gas contained simultaneously in mudstone, shale and other similar formations in both absorbed and free states [1–3]. Different from natural gas contained in tight sandstone formations, shale gas is characterized by longer production life, prolonged production duration, fast declination of pressures and productivities. Shale gas wells, with low well productivity, reveal high wellhead pressures, and some wells may produce gas field water and condensate oil. All these features are significantly different from reservoir features and wellhead physical properties of conventional natural gas reservoirs, and they are key factors that may directly affect surface processes. Accordingly, surface engineering conditions for share gas are also different from those in conventional gas fields [4].

Since pressures and productivities vary significantly from early stages to middle and later stages of shale gas development, surface facilities are required to have desirable adaptability. To meet the requirements of large-scale development of shale gas with low costs and high efficiencies in China, surface engineering facilities for shale gas development should be designed in accordance with the principles of "standardized design, modularized construction". Simplified and optimized working modes should be adopted to facilitate shale gas development in China [5–7].

1. Design difficulties

Still in its starting stage, shale gas development in China is predominantly based on technologies deployed for the

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Peer review under responsibility of Sichuan Petroleum Administration.

http://dx.doi.org/10.1016/j.ngib.2016.02.009

development of conventional natural gas, with poorly developed surface gathering and transportation technologies, no sophisticated management system or no sufficient industrial standards. More explorations and summarization of experiences are required for the development of auxiliary surface supporting technologies. Generally, some difficulties should be considered in the surface engineering design in shale gas development.

1.1. Uncertainties in the capacities of a gathering and transportation system

In general, shale gas fields are characterized by high productivity in early stage, fast decline in productivity in late stage, and significant changes in productivity in the life cycle. Data from several shale gas fields in US show that approximately 80% of total production for one shale gas well may be completely recovered within 10 years, and total production remains steady at a low level. These features are different from those of conventional natural gas fields, which are characterized by steady overall productivity and lower production decline rates [8,9]. Consequently, uncertainties in capacities of surface gathering and transportation system represent a key difficulty in design. Since most shale gas fields are developed in rolling manner, difficulties in the accurate prediction of the increased productivities in later stage make it even harder to clarify the capacities of surface gathering and transportation systems to be designed.

1.2. Poor adaptability of pipeline network and station layout

In conventional gas fields, surface engineering design of gathering and transportation pipeline networks and stations can be easily performed in accordance with the development program and the performances of individual wells. However, since productivities of shale gas fields vary significantly, capacities of surface gathering and transportation systems and layouts of stations are required to be adjusted continuously to cope with the changes in productivities. Consequently, it is difficult to determine the capacities of pipeline networks and the layouts of stations. To meet the requirements for long-term development, the networks and layouts should be adapted and adjusted continuously.

1.3. Difficult matching of process facilities

Key technologies for the development of auxiliary surface engineering in shale gas development are closely related to the features of gas reservoirs. To ensure normal production, shale gas fields should be developed in scale with large areas. Under such circumstances, “factory-like” around-the-clock operations may require close matching in the construction of surface engineering facilities. As was mentioned above, significant changes in pressures and difficulties can be observed in early and late stages of shale gas development, and the capacities of gathering and transportation facilities are required to change accordingly. Since it is quite difficult to match process facilities, those with desirable adaptability should be deployed [10]. In this way, skid-mounted facilities that can be easily relocated and installed should be used. In addition, standardized and modularized design should be adopted for surface process facilities to provide desirable capacities and operation flexibilities through fast adjustments to satisfy the demands of relevant stations.

1.4. Demands for pressure boosting in later development stage

Development of shale gas fields is characterized by extremely high wellhead pressures in early stage and fast pressure drop in later stage. These features are significantly different from those in conventional gas fields. Since shale gas fields may be under prolonged low-pressure conditions in later stage, pressure boosting should be considered as a difficulty in shale gas development. Besides, pressures in early stage of shale gas development should be fully utilized if possible [11]. With consideration to changes in pressures and productivities of gas fields, designed capacities and pressures of the gathering and transportation systems should be adjusted to cope with the pressure changes in later stage and to balance the volumes of gas among different stations.

2. Core technologies in standardized design

Standardized design of surface engineering can effectively shorten the time required for construction, minimize construction cost and ensure the quality of surface engineering facilities [12,13]. With consideration to similar station layouts, process flows and facilities in surface engineering construction in oilfields and depending on specific surface conditions, designs with uniformed standards, process flows and modularized facilities should be performed to generate one package of design patterns characterized by standardization, codification and universality.

Standardized design of surface gathering and transportation facilities in shale gas fields should be made in accordance with the overall process flow of “Cluster well site–Gathering stations–Central processing station–Export”. During the course, surface technologies such as “high-pressure gas production, medium-pressure gas gathering, wellhead heating and throttling, import gas from cluster wells to the station, centralized dehydration and pressure boosting in later stages” can be deployed. Based on the successful applications of standardized design of surface gathering and transportation facilities in shale gas fields in US, a standardized design suitable for surface gathering and transportation facilities in shale gas fields in China has been developed to ensure high-efficiency production allocation and low-cost development. Core techniques in the design can be summarized as follows: standardized well station layout, universal process flow, modularized function zoning, selection of skid-mounted facilities, serialized combinations of facilities, intensive site design and digitized production management.

2.1. Standardized well-site layout

In accordance with the "well factory" mode for the development of shale gas, a cluster horizontal well platform with 2–6 wells are deployed on the well site. As for the layout and planning of the well site, standardized layout is promoted to minimize land occupation and capital investment without sacrificing the designed capabilities of such stations. For the purpose of standardized design, the positions, capacities, supporting devices and signs in all well sites and gathering stations are designed and constructed in a coordinated manner [14] to promote integral organization, stream-lined operations and standardized work site.

2.2. Universal process flow

During the development of shale gas fields, blocks with trial productions are developed in preference. Generally, these gas fields are developed in accordance with the overall program and in a rolling development mode. Under the "well factory" mode, standardized sites for cluster wells can be constructed to accommodate high-efficiency gathering and transportation facilities. As for surface gathering and transportation techniques, universal process flow design is adopted. For cluster well platforms with different number of wells, process flows in well sites and gathering stations are optimized and simplified. Besides, coordinated process flow and capacities should be guaranteed in well sites and gathering stations, with compatible models of facilities, so as to facilitate planning and management in later stage.

2.3. Modularized function zoning

For obtaining high-efficiency production allocation, shorten construction duration and minimize investment cost, modularized design of gathering and transportation stations can be performed in accordance with standard process flows for well sites and gathering stations. All cluster well platforms and gathering stations can be divided into independent modules in accordance with function zoning principles. All such modules should have desirable universality. Such division may make standardized modularized management in minor scales possible and facilitate modularized combination of relevant design drawings. In addition, 3D software can be deployed to optimize 3D piping design of such station modules [15].

2.4. Selection of skid-mounted facilities

Key techniques for auxiliary surface facilities in shale gas development are closely related to the specific features of gas reservoirs to be developed. With smaller size, skid-mounted facilities can be easily relocated and deployed through combination. Since shale gas fields may experience significant changes in pressures and productivities in early and later development stages, construction of mobile skid-mounted surface facilities can effectively promote the development of shale gas fields [16]. Deployment of skid-mounted facilities should be used, if possible, on cluster well sites and in gathering stations to ensure highly effective utilization of such process facilities. As far as models of skid-mounted facilities are concerned, universal pipelines, valves, fittings, configurations and technical specifications should be deployed to establish a solid foundation for large-scale procurement.

2.5. Serialized combinations of facilities

It is difficult to clarify the designed capacities of surface gathering and transportation facilities in shale gas fields. Nevertheless, serialized processing facilities can be deployed. For example, stand-alone facilities with the designed annual capacities of 10×10^4 t, 15×10^4 t and 30×10^4 t can be fabricated. Later, these facilities can be deployed in combination in different phases with high flexibility in accordance with changes in productivities and scope of processed media. In this way, construction costs can be reduced significantly. In addition, demands of long-term gathering and transportation operations can be satisfied. Thus, the proposed working mode can be seen as the key technique required for the surface engineering facilities deployed in shale gas fields. The working mode is worthy of promotion.

2.6. Intensive site design

With consideration to the "low-carbon emission" concept, all work sites should be designed in an intensive manner to ensure a proper utilization of relevant resources. With surface facilities deployed rationally, maximum utilization efficiencies can be achieved for such gathering and transportation process facilities. In this way, low investments, low consumptions and high productivity can be achieved in the construction of surface engineering facilities. Designs of all sites and stations, including sings, road structures, plane distribution, access roads, should be constructed and managed in a standardized manner to promote harmonious coexistence with surrounding environments [17].

2.7. Digitized production management

Automatic, informational and modern management should be performed in shale gas fields to promote production and safety management and to minimize labor costs. As an integral component in oil/gas field exploration development, construction of digitized oil/gas field can effectively enhance operation efficiency, optimize production process, promote HSE performances, minimize production costs, elevate investment return rates and accumulate intellectual properties. Comprehensive database, informatization management platform, integrity management system and 3D visualization displaying system are established for data acquisition and real-time monitoring of surface gathering and transportation system. In this way, an "integral" management and an auxiliary decision-making platform for the full-life management of surface engineering facilities can be established.

3. Field application

3.1. Background

Exploration and development of shale gas fields in the Sichuan–Chongqing area are far ahead of those in other areas in China. With reference to the successful experiences in the exploration and development of shale gas fields abroad, the state-of-the-art standardized design techniques have been deployed to study and review the standardized design in shale gas fields. The "standardized & modularized & skid-mounted" design of surface engineering facilities has been promoted in shale gas fields to establish a unique exploration and development system suitable for domestic shale gas fields. A series of standardized processes and modules have been designed for platforms of cluster wells, gathering stations and supporting facilities. These achievements are meaningful for the technical progresses in the development of domestic shale gas fields in the future. In addition, models for large-scale and low-cost development of shale gas in China were established. The following sections will discuss the application of standardized design of surface engineering facilities in a shale gas field in the Sichuan–Chongqing area.

In accordance with the overall development program and the requirements for shale gas development, the standardized design of surface engineering facilities should conform to regional geologic conditions and physical properties of shale gas. In addition, these facilities should be designed uniformly but constructed in different phases to satisfy the demands in Phase 1 and with consideration to demands in later phases. During the system design, conditions in both upstream and downstream sectors should be considered to achieve safe, environmentally-friendly and high efficiency performances. Standardized design of surface engineering facilities should be performed in accordance with specific conditions in the concerned gas fields to minimize land occupation, standardize process flow, to develop serialized facilities, universal devices, skid-mounted facilities and digitalized management of surface engineering facilities in the development of shale gas fields.

3.2. Technical principles for ground surface engineering

3.2.1. Gathering and transportation flow

Natural gas produced from wellheads is delivered to gathering stations through gathering pipelines. Within a gathering station, the natural gas experiences two-stage heating, two-stage throttling, metering and separation before being exported. The exported natural gas enters the trunk gathering line through branch lines before further transmission into a central processing station for centralized separation, heating, and TEG dehydration. Eventually, the resulting dry gas is metered and delivered to distribution stations of a natural gas company for final delivery.

3.2.2. Gathering and transportation processes

Natural gas is transported in wet manner. It is heated at the gathering station to prevent natural gas hydrates from being formed. In addition, glycerol injector is preserved in the gathering station. De-sanding process is deployed on the wellhead with alternating metering operations. Contaminated water in the gathering station is pumped into above-head water tanks before being delivered to secondary water-supplying pumps via water tanks for re-utilization. The gathering and transportation pipeline network is equipped with glycerol injection and pigging facilities. Skid-mounted process facilities with modularized design are used in the gathering and transportation station. In addition, standardized process flow is deployed in the station.

3.2.3. Gathering and transportation pipeline network

In accordance with the distribution features of gas reservoirs and requirements specified in the development program, and for coping with the uncertainties of pressure changes in shale gas fields, pipeline network with "radial + circular" configuration is recommended. With satisfactory overall safety performances and high flexibility, this kind of network can satisfy the demands of specific gas fields. It is worth mentioning that this network can effectively balance gas volumes among different dehydration stations, and consequently, can satisfy demands for long-term plans for the development of shale gas fields.

3.3. Design of standardized process flow

Standardized process flow is deployed on well sites and in gathering stations to establish standardized sites with integral organization and standardized process flow. In view of the deployment of wells on platforms, standard gathering stations with 2, 4, 5 and 6 wells can be constructed independently. See Fig. 1 for the standardized process flow in different sites and stations.

3.3.1. Standard process flow of the two-well platform

Facilities in gathering stations with two wells are deployed in one train, i.e. Incoming gas from wellhead to Heating → Separation → Metering, with one package of processing facilities deployed for one well. Heater in the stations contains dual coils with heating capacity of 200 kW. Metering separator with pipe diameter of 800 mm is deployed for gas–liquid separation and metering. See Fig. 2 for the standardized process flow in wellhead and gathering stations of the two-well platform.

3.3.2. Standard process flow of four- and six-well platforms

Wellheads in four- and six-well platforms have similar processes. Exceptionally, the four-well platform is equipped with two heaters with four coils and capacity of 400 kW, while the six-well platform is equipped with three heaters with four coils and capacity of 400 kW. Both four- and six-well

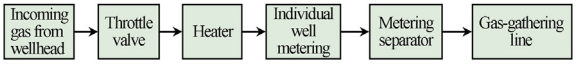

Fig. 1. Wellhead gas gathering process flow.

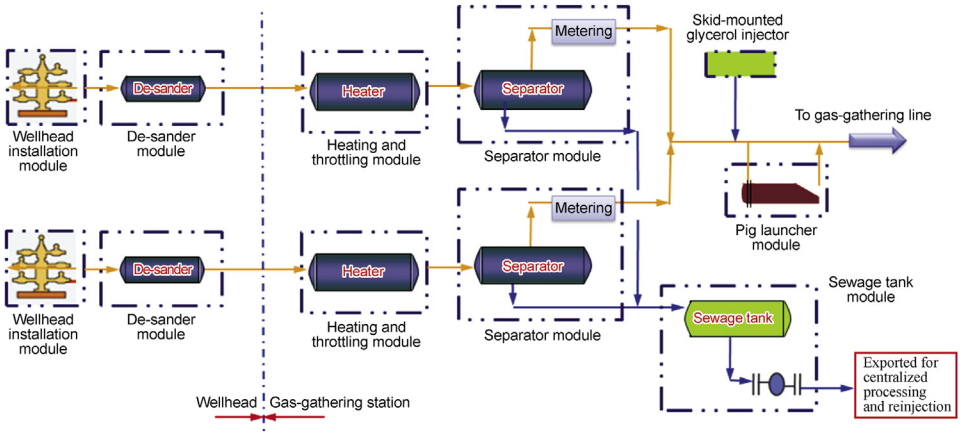

Fig. 2. Standard process flow of two-well gathering stations.

platforms are equipped with a metering separator (with pipe diameter of 800 mm), respectively. In addition, a production separator (with pipe diameter of 1200 mm) is deployed for gas–liquid separation in other wells. See Fig. 3 for the standardized process flow in wellhead and gathering stations of four- and six-well platforms.

3.4. Modularized design of gathering and transportation stations

For high-efficiency production allocation, construction time reduction and investment cost saving, universal modules and skid-mounted modules are deployed in the standardized well site design. When the incoming gas from cluster well sites enters the gas gathering module in the station, pressures are measured to determine if pressure boosting is required. Then, after gas–liquid separation, the gas is metered and eventually delivered to the dehydration station for processing. Different process modules can be deployed in combination to achieve various functions in the process flow of such stations. See Fig. 4 for the modularized process flow in gathering stations.

In accordance with the standardized process flows in wellheads and gathering stations, identical components in wellheads and gathering stations are divided into separate modules. In addition, each function zone is separated into independent, standard miniature modules. These modules are independent of each other and connected through pipeline network to facilitate a modularized combination of design drawings and pre-fabrication on sites. The wellhead and the gathering station can be divided into 11 modules, including wellhead installation, de-sander, heater, metering separator, production separator, glycerol injection, fuel-gas pressure regulator, pressure booster, sewage tank, manifold and pig launcher. Particularly, the heater, separator and glycerol injector are skid-mounted. All such modules have pipelines designed in 3D. See Table 1 for the classification of process modules and function zoning on well sites.

3.5. Serialized design of dehydration facilities

In view of the process flow, the incoming gas in gathering stations is delivered to the dehydration station for purification

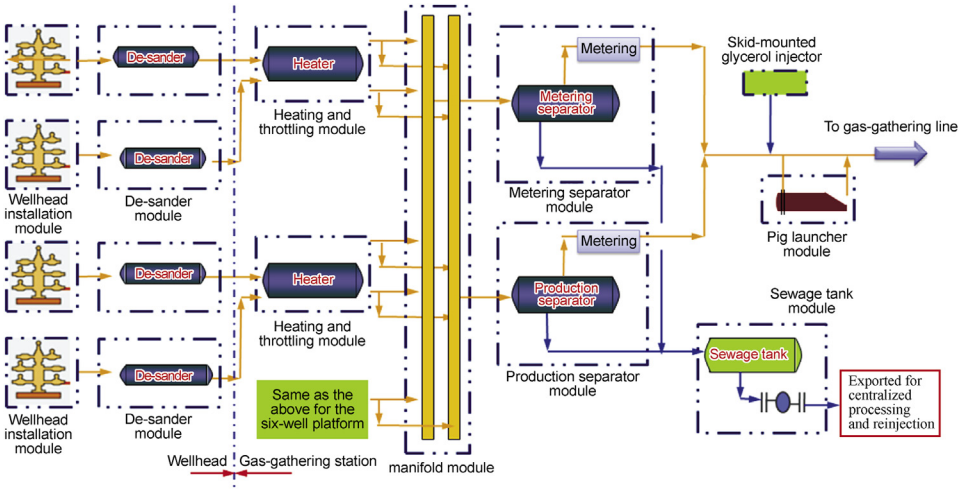

Fig. 3. Standard process flow of four- and six-well gathering stations.

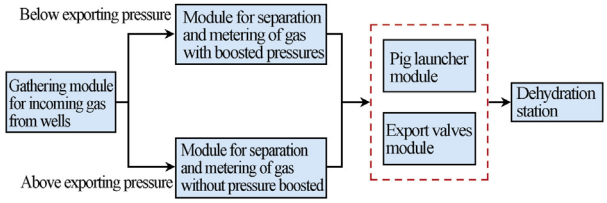

Fig. 4. Modularized process flow in gathering stations.

through gathering and transportation pipelines. During the course, TEG dehydration facilities are used for dehydration. Natural gas firstly enters the filtering and separating device to remove all possible free liquids and mechanical impurities. Then, it is heated to 20 °C in the heater before entering dehydration facilities. Purified gas out of dehydration facilities is metered and delivered to individual users with pressures properly regulated.

Individual processing devices with fixed configurations can be combined and assembled to trains of processing facilities of various types and different capacitates. Dehydration facilities in dehydration stations are deployed in trains, with all major devices skid-mounted. These trains of facilities can be installed in separated stages with high flexibility to cope with specific production performances. Dehydration facilities can be designed with a combination of the two processing capacities of 15×10^8 m^3/a and 40×10^8 m^3/a.

The dehydration station with a total processing capacity of 15×10^8 m^3/a contains two trains of dehydration facilities, which should be used in combination. One train of dehydration facilities with a processing capacity of 10×10^8 m^3/a is constructed and the other train of dehydration facilities with a capacity of 10×10^8 m^3/a is preserved. See Fig. 5 for more details related to the configurations of such facilities.

According to the overall development program, the 40×10^8 m^3/a dehydration station is equipped with dehydration facilities with individual capacity of 10×10^8 m^3/a after the expansion of processing capacities. Three trains of dehydration facilities with a capacity of 10×10^8 m^3/a each are combined and one train of dehydration facilities with a capacity of 10×10^8 m^3/a is preserved. See Fig. 6 for more details related to the configurations of such facilities. Since the commissioning of the system, dew point of the dehydration processes has been enhanced to −17 °C.

3.6. Intensive plan layout of the site

In the Sichuan–Chongqing area, development of shale gas fields is based on the experiences abroad to accomplish intensive site design. With proper planning and centralized construction, the design is favorable for the minimization of land occupation and environmental protection. With regard to plan distribution of “well factory” cluster well sites, the combination of the well site and gathering stations (with “L” and rectangular configurations) has been proposed depending on the demands for drilling and trail production operations. Such combination can effectively minimize land occupation

Table 1
Process modules for wellheads and gathering stations.

S/N	Module	Function	Specifications of equipment in the gathering station		Remarks
			Two-well layout	Four-, five- and six-well layouts	
1	Wellhead installation	Wellhead emergency shutdown, pressure & temperature display and transmission			
2	Wellhead de-sander	Sand removal for incoming gas from wellhead	With pipe diameter of 65 mm	With pipe diameter of 65 mm	
3	Heater	Heating and throttling of incoming gas from wellhead	Only one heater with capacity of 400 kW	Two, two and three, respectively heaters each with capacity of 400 kW	Skid-mounted
4	Metering separator	Gas–liquid separation and metering of incoming gas from wellhead	With pipe diameter of 800 mm (1 separator)	With pipe diameter of 800 mm (1 separator)	Skid-mounted
5	Production separator	Gas–liquid separation	N/A	Production separator with pipe diameter of 1200 mm	Skid-mounted
6	Glycerol injector	Inhibit formation of hydrates			Skid-mounted
7	Fuel-gas pressure regulator	Fuel-gas separation and pressure regulation			
8	Pressure booster	Centralized pressure boosting of incoming gas from wellhead			Skid-mounted
9	Sewage tank	Sewage water storage	With storage capacity of 10 m^3	With storage capacity of 10 m^3	
10	Manifold	Metering and production manifold	N/A	With pipe diameter of 100 mm for four- and five-well layouts & 200 mm for six-well layout;	
11	Pig launcher	Pipeline pigging operations	With diameter of pig launcher of 100 mm	With diameter of pig launcher of 150 mm	

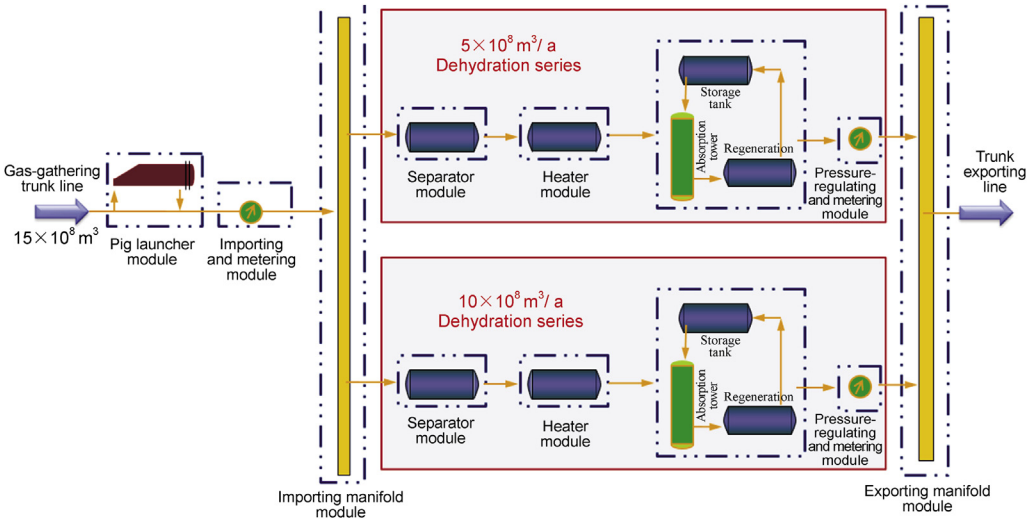

Fig. 5. Standard process flow of a dehydration station with a capacity of 15 × 10^8 m^3/a.

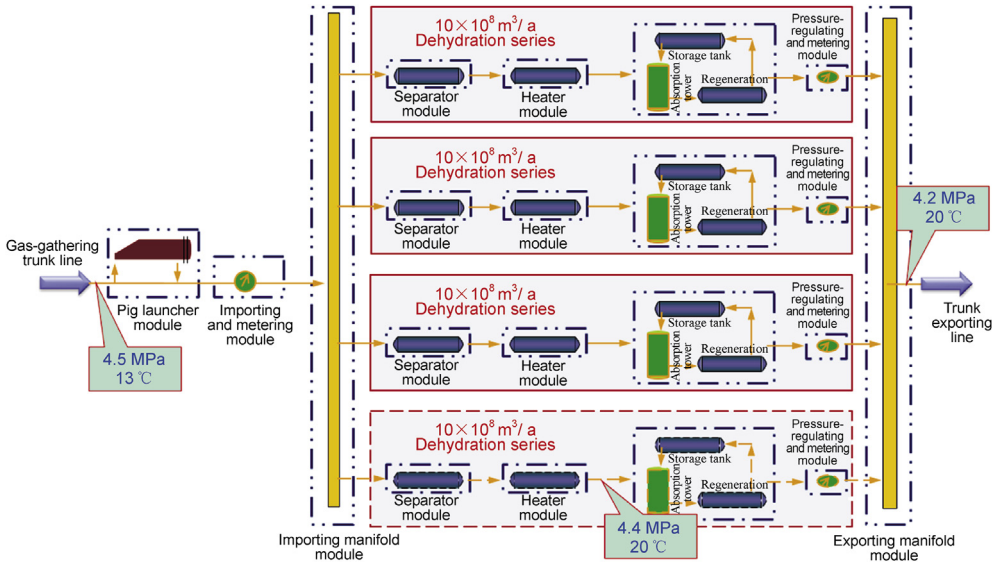

Fig. 6. Standard process flow of a dehydration station with a capacity of 40 × 10^8 m^3/a.

and reduce difficulties in management over the well site and the gathering station.

Gathering stations for shale gas fields belong to Level-V stations classified according to their production scale (See GB 50183-2004 Fire Code in Oil & Gas Engineering Design). For their general layout, fire clearance for process facilities should be designed accordingly. The specific clearance should be determined in accordance with the process features, classification of fire hazards, functional requirements, landforms, prevailing wind directions and other specific conditions. See Figs. 7 and 8 for the plane layout of standardized gathering stations.

3.7. Standardized design performances

Through standardized design of the surface engineering facilities in shale gas fields in the Sichuan–Chongqing area, integral design of surface engineering, exploration and development can be made in unconventional gas fields. During the implementation of the innovative design, guidelines with "engineering conditions conform to geologic conditions, surface conditions conform to underground conditions; combination of geologic and engineering conditions and combination of underground and surface conditions" are closely observed.

Presently, the shale gas block has constructed a drilling platform of "well factory". With factory-like operation modes, standardized gathering stations can be constructed together with the expansion of the drilling platform. Gathering and transportation pipeline network among the existing platforms, gathering stations and dehydration stations should have "radial + circular" configuration. A transmission capacity of the newly-constructed gathering pipeline network should be

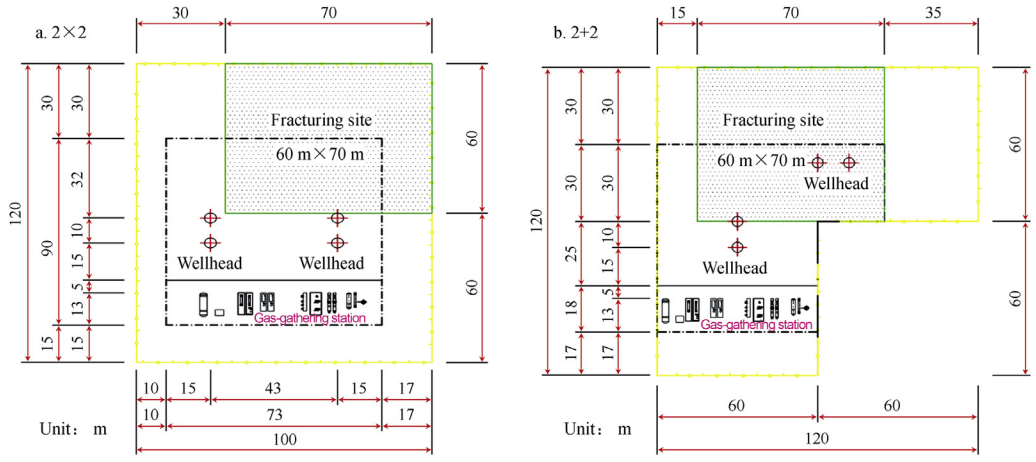

Fig. 7. Layout of 2 × 2 and 2 + 2 well sites and gas gathering stations.

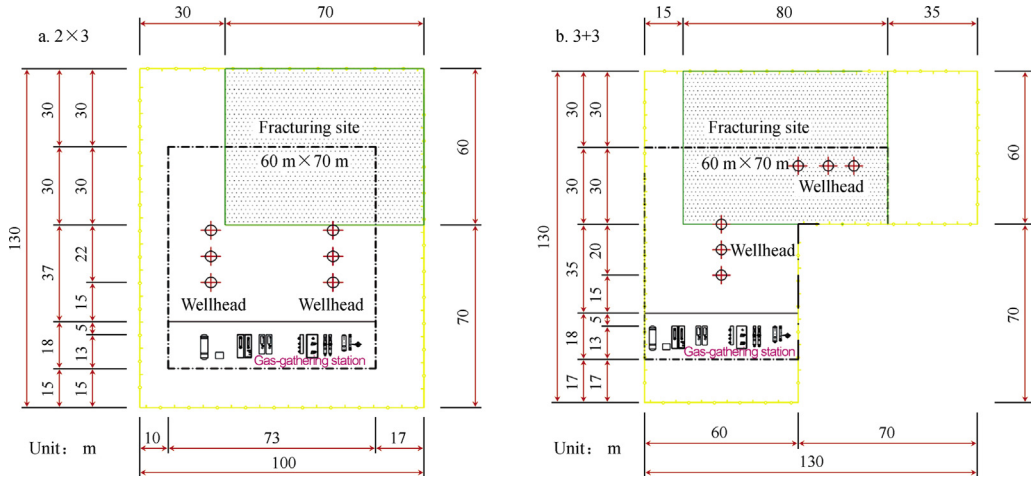

Fig. 8. Layout of 2 × 3 and 3 + 3 well sites and gas gathering stations.

50×10^8 m^3/a. Generally, surface gathering and transportation facilities for the block are deployed in two levels, namely, "sites of cluster wells for gas production – gathering stations – dehydration station". In this way, standard gathering and transportation process flows involving skid-mounted facilities can be established. The entire gas production, gathering and transportation process contains two-stage de-pressurization and two-stage dehydration processes accomplished by 8 independent standard modules in combination. As required to "minimize land occupation to construct the demonstration zone", area occupied by each individual well may be reduced by more than 30%. In addition, the gas field promotes duplicity and universality of relevant engineering techniques. Generally, a series of standardized construction codes and technical specifications have been produced to facilitate standardized design, construction, procurement and informatization management.

4. Conclusions and suggestions

1) Certain progresses have been achieved in shale gas development, gathering and transportation technologies in China. However, there are still big gaps with those techniques deployed abroad, and there is no complete system thereof. Development of shale gas fields in China is based on successful experiences from other countries to achieve "low-carbon emission". Accordingly, sufficient attentions should be paid to the protection of the ecologic environment and support for more eco-friendly projects. With "cluster wells" design, "well factory" operation mode, "standardized" design and rehabilitation, area of land occupation has been significantly reduced.

2) By promoting standardized design of surface engineering facilities for shale gas development, innovative designs of surface facilities have been developed depending on the specific demands in shale gas fields and for the construction of surface facilities. The conventional "large and all inclusive" and "small but all inclusive" design principles have been replaced by the construction of surface production system with high flexibility, practicability and reliability. With surface and underground facilities optimized and designed uniformly, high-quality, high-efficiency, safe and state-of-the-art engineering designs can be achieved. In fact, these designs highlight the development trend in the

construction of surface facilities in large-scale oil/gas fields. Surface gathering and transportation facilities for shale gas in China are progressing in the direction of limited land occupation, standardized process flow, serialized devices with high university, skid-mounted facilities and digitalized management.

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