THEORY AND PRACTICE OF OIL AND GAS FIELDS DEVELOPMENT

PHYSICAL EXPLANATION OF THE RETROGRADE CONDENSATION PROCESS IN THE GAS-CONDENSATE RESERVOIR CONDITION

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The paper studied the phase behavior of the gas-condensate systems in the porous media. Special experimental investigations and theoretical analyses have been conducted for learning the colloidal characteristics of the gas-condensate systems and its importance in reservoir condition. Using this obtained information a new explanation about the nature of the condensation process was given and also some theoretical aspects were detailed differently. The conclusions were tested and proven on the natural gas-condensate reservoir in accordance with analysis of real gas-condensate producing well performance.

Introduction

Gas-condensate reservoirs exhibit complex phase and flow behaviors during the depletion of the reservoirs. It associates a loss of valuable condensate fluid in the reservoir and also results in appearance of condensate banking in the near well region. A good understanding of the effect of the changing composition on the flow and phase behavior properties of these reservoirs is essential for carrying out accurate forecasts of the performance of gas condensate reservoirs (Raghavan, Jones, 1996; Katz, Kurata, 1940). Usually the phase transitions of gas-condensate systems are studied in PVT cells which are free from porous media and may affect the quality of results (Chatenever, Calhoun, 1952). Also the dew point pressure of the system which is very important for projecting the exploitation of the gas-condensate pool could be determined incorrectly.

Investigation the effect of porous media on gas-condensate phase behavior or dew point pressure has been studied since middle of last century (Chatenever, Calhoun, 1952; Razamat, Mardakhaev, 1976; Sigmund et al., 1973). Most of the obtained experimental data have proved that the phase behavior of the gas-condensate systems in the reservoir model is entirely different from the PVT cell which is porous media free vessel. In other words, the retrograde dew point pressure of gas condensate system is higher in the porous media than in the porous free media PVT cell (Trebin, Simako, 1977).

Researchers confirm that there are many aspects: condensate/gas ratio, condensate density, thermodynamic condition, lithological properties of the formation etc, should be considered for deeper investigation this phenomenon. Also, connate water in the porous media, it's physical and chemical feature, porosity and the specific surface of the formation granular could be very important factors (Abasov et al., 2013; Abbasov, Fataliyev, 2015; Trebin, Zadora, 1968).

In recent years, there are many papers have been published which related to this subject. All of them emphasize the importance of this phenomenon regarding the gas-condensate field exploitation and development (Abasov et al., 2013; Abbasov, Fataliyev, 2015; Li Mingjun et al., 2008; Mirzadzhanzade et al., 2003). One of the detailed investigation was carried out by us which covered in these papers (Abasov et al., 2013; Abasov et al., 2009). We analyzed all effected parameters and selected those parameters (pressure, temperature, specific surface and porosity of porous media, amount of connate water and condensate density) which have significant role in this exercise. Rational mathematical methods were used for modeling gas-condensate reservoir condition, depletion process of the gas-condensate reservoir and also for planning experiments. The advantage of this study is a mathematical equation was obtained which presented the correlation between the effected parameters. However, this investigation could not explain the physical or thermodynamic nature of the effect.

In the paper (Abbasov, Fataliyev, 2015), we tried to explain the mechanism of the depletion process in the porous media. Experimental investigations on groups of gas-condensate samples from Azerbaijan natural gas-condensate reservoir confirmed that two phases-gas and condensate can be flowing to the well even when reservoir pressure is higher than retrograde dew point pressure of reservoir fluid. This phenomenon can cause condensate blockage or condensate banking on the early stage of reservoir development, results from a combination of different factors. Theoretical and experimental data was summarized, the gas-condensate system was analyzed as a colloidal-dispersion solution and identified that retrograde condensation in porous media can be caused by break off the Brownian motion due to absorption process between sub-micron-sized condensate particles and formation rock granular surfaces.

Summarizing all results of existing works show that the phase behavior of gas-condensate fluid in the reservoir condition plays a significant role in the deliverability evaluation and in the forecasting of gas condensate fields. If neglecting its effect on the deliverability, gas and condensate production rates could not be accurately predicted. In this sense it is very important to understand the mechanism of the retrograde process in the reservoir conditions (Abasov et al., 2005; Ke-Le Yan et al., 2013). Some valuable points related to this issue have been explained in works (Abasov et al., 2009; Razamat, Mardakhaev, 1976) however full explanation has never been given and in-depth study is required.

In this work, a new approach is displayed to explain the physical features of the retrograde condensation process in the porous media. The issue is analyzed base on experimental and theoretical investigations. Using this obtained information a new explanation of the process was given and some theoretical aspects were detailed differently. Also the theoretical conclusions were tested and proven on the natural gas-condensate reservoir in accordance with analysis of real gas-condensate well performance.

Experimental apparatus and procedure

Experiments have been carried out on УГК-3 type of PVT bomb which is standard apparatus designed for determining thermodynamic characteristics and phase behavior of gas condensate systems (Zotov, Aliev, 1980). Maximum working pressure is 45MPa, maximum working temperature is 80^0C and cell volume is $3x10^{-3}$ m^3. The PVT cell is composed of an efficient magnetic fluid mixer mounted on the piston, a dedicated visual head, two sampling valves, an accurate pressure transducer and an electric heater for homogeneous temperature control. In addition, the original design has been slightly modified within the safe operating limits. In order to perform or to model reservoir depletion process and constant composition expansion test in the high temperature range, a heat exchanger was installed to increase working temperature of the bomb up to 110^0 C. Also this unit linked with nitrogen bottles and vacuum pumps which are used for purging, cleaning and preparing the cell for preservation or next operation.

An eyeglass permits observation of the fluid behavior through the cell windows. During Constant Composition Expansion-CCE or Differential Condensation-DC testes, the changes of the gas and liquid phases are observed by the full visibility of the gas/condensate interface through the window of the cell. CCE and DC test procedures are stated in the work (Zotov, Aliev, 1980).

The reservoir model was designed in accordance with mathematical criteria. Porous media composition and other aspects were comprehensively described in the paper (Abasov et al., 2013).

Results and discussions

The colloidal feature of the gas-condensate system

The study of the phase behavior of fluid at high pressure has been mainly restricted to mixtures containing either two or three components. Our understanding of fluid phase equilibria has almost exclusively relied on experimental observation and calculations have only played a relatively minor supporting role. This is likely to change when ternary and other multicomponent mixtures are considered. The most fascinating aspect of high pressure equilibria is perhaps the diversity of critical transitions (Sadus, 1992). It is a common knowledge that a thermodynamic state of fluid is specified by thermodynamic parameters or variables e.g. pressure, temperature, volume, the mole fraction of one of its components (Deiters, Kraska, 2012). If one of these parameters changes in equilibrium condition the system moves to next thermodynamic state. If this change results in phase transition then at first micro embryos of the new phase appears and then they slowly growth as accordance leading parameters. This phase transition mechanism was studied and confirmed by many famous scientists (Mirzadzhanzade et al., 2003). That means, this process is applicable for gas-condensate systems as well. In order to learn the forming of the liquid phase in the gas-condensate mixture near the retrograde condensation region, specific experiments were carried out. УГК-3 type of PVT bomb was used for that. Samples were taken from Azerbaijan gas-condensate field "Bulla-deniz". The reservoir fluids were then prepared in the laboratory by recombining the separator condensate with the separator gas according to the gas/condensate ratio data, based on a standard analytical method for condensate gas properties (Abasov et al., 2013; Zotov, Aliev, 1980). The composition of the gas is C_1-91.61, C_2-4.79, C_3-1.41, C_4-1.64, C_5-0.53, C_6-0.02% and gas density is 0.7322kg/m^3. Condensate density is 745.7kg/m^3 and condensate/gas ratio of recombined gas-condensate system is 250g/m^3.

A constant composition expansion (CCE) test was performed to determine the retrograde dew point-RDP pressure and liquid dropout behavior of the fluid. In this work, similar experimental phenomena for the CCE test monitored through the windows of the PVT cell for gas-condensate systems. As an example, here is the description of our observations when we introduced the process at a temperature of 100^{0}C during the CCE test.

The prepared sample was pressurized to above the dew point pressure-28MPa in isothermal condition. The fluid was a single phase that was transparent and pale yellow in color. As the CCE test proceeded and the pressure dropped, the color of the reservoir fluid also changed gradually from pale yellow to pale red. When the pressure was decreased to close to 24.6MPa the fluid began to fog up. This pressure accepted as a fog up pressure-FUP. Then the fog thickened with decreasing pressure. The convective phenomenon of the thick fog was observed by the naked eye through the PVT cell window. With a continuous drop in pressure, a tiny liquid drop precipitated, at the corresponding pressure-22.68MPa which was the retrograde dew point pressure-RDPP of the gas-condensate system. In this group of experiments, the FUP and RDPP were determined at the different temperatures. These data allowed us to define the correlation between FUP, RDPP and temperature which is presented in fig. 1.

As shown in the Fig. 1, there is a significant difference between FUP and RDPP, also the deference is increasing with the increase of temperature. It is known that microscopic particles of one phase dispersed in another are generally called colloidal solutions or dispersions (Pashley, Karaman, 2004). It means that the fog which we observe in gas-condensate system is colloidal state of system. In this case the gas is dispersion medium and condensate is dispersed phase. If pressure decreases at a constant temperature, surface energy of dispersed phase increases and creates an environment for coalescing fine condensate particles.

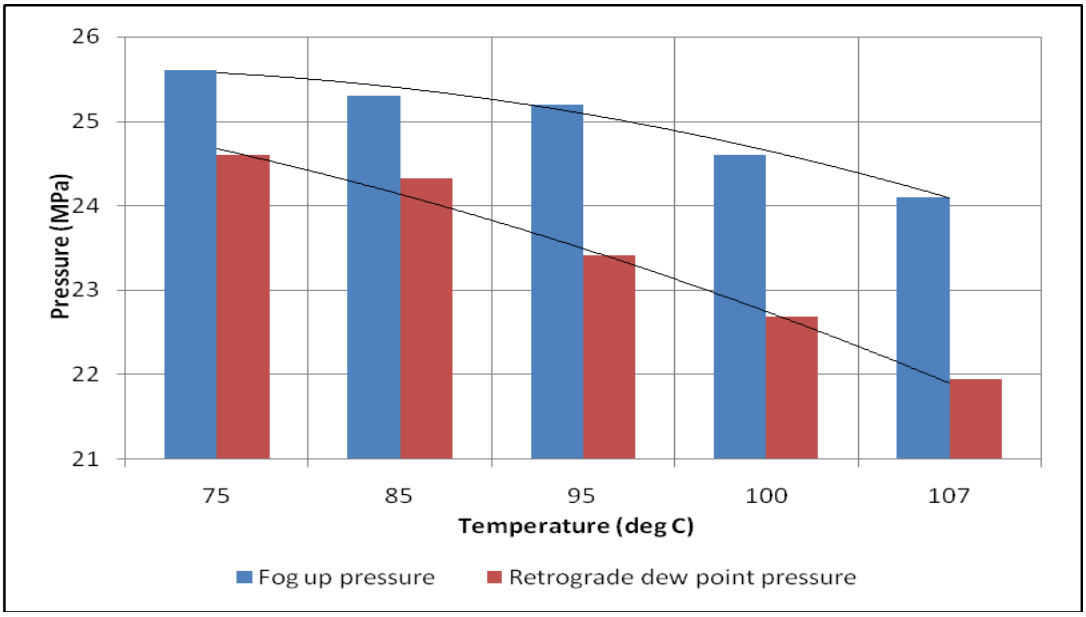

Figure 1. Variation of the fog up and retrograde dew point pressures during constant composition expansion test on gas-condensate systems at different temperatures.

These sub-micron-sized particles grow following pressure drop and turns into aerosol-colloidal state which can be seen as the fogging up process. Also increasing the deference between FUP and RDPP with the increase of temperature can be considered well-matched with the properties of colloidal substances.

In line with this conclusion, it can be assumed that it is the reason why a given constant temperature retrograde dew point pressure of the gas-condensate system in the porous media is higher than in the free cell. In other words retrograde condensation can happen even the liquid phase is in the early or embryo state (Abbasov, Fataliyev, 2015; Razamat, Mardakhaev, 1976). Fog state of the system could be a very suitable condition for intermolecular forces around a molecule in the liquid embryos and formation granular surfaces to dominate liquid to be dropped out at the pressure higher than it was identified in the porous media free PVT cell.

The physical nature of the phase transition in reservoir condition

Understanding the physical nature of this process can play a particularly vital role in gas-condensate reservoirs. Condensate liquid saturation can build up near a well because of early condensation and the near-well choking can cause unstable operation. For more learning this proposition, we used an experimental data which provided in the paper (Abasov et al., 2009). Their intention was to identify the impact of porous media on condensate recovery factor, however some useful information was there that allows a comparison of a couple of experiments that were carried out in parallel on reservoir model and free PVT cell.

Samples were taken from Azerbaijan gas-condensate field "Bulla-deniz". The reservoir fluid was then recombined in the laboratory environment. The composition of the gas was C_1-93.5, C_2-4.2, C_3-1.24, C_4-0.65, C_5-0.14, C_6-0.05, CO_2-0.22%, C_{5+}-6.02 g/m^3 and gas density was 0.7243 kg/m^3. Condensate density was 737.9 kg/m^3 and condensate/gas ratio of recombined gas-condensate system was 200 g/m^3.

The prepared sample was pressurized up above the RDP pressure-30 MPa at a temperature of 100^{0}C as per procedure. The fluid was a single gas phase state. Same temperature and pressure were maintained in the reservoir model using heat exchanger and high pressure nitrogen bottle. In the thermodynamic equilibrium condition, the gas-condensate system was squeezed from PVT cell to the reservoir model and nitrogen replaced slowly. It was continued until same fluid composition was confirmed in the model. Then reservoir model was isolated from PVT cell without disturbance of equilibrium condition. Depletion regime was modeled on both vessels using differential condensation-DC procedure. The amount of gas and condensate which were removed from the system, were measured in the separator. Separation pressure-5MPa and temperature-22^{0}C were maintained during the experiments. These set points were identified as a maximum liquid drop out condition as per special experimental trials which had been carried out before this experimental study. It is required depletion rate to be maximum 8.33-16.67x10^{-6} m^3/sec for two reasons: to maintain thermodynamic equilibrium condition in the PVT cell/reservoir model and to maintain optimal separation condition in the separator. Gas chromatography was used to analyze hydrocarbon compositions. FUP and RDPP were identified 26.4MPa and 24.3MPa respectively in the PVT bomb. Results are given in the fig. 2.

As it is shown in the fig. 2 retrograde condensation pressure in the reservoir model is higher than in the PVT bomb. After applying empirical and graphical analyses the gas-condensate system RDPP has been identified 29MPA in the reservoir model (Abasov et al., 2009). It proves that retrograde condensation of gas-condensate system can start above the aerosol/fog state of the system in porous media condition.

One of the interesting points in this fig.2 is we can see that retrograde condensation process accelerates in the reservoir model when pressure is below RDPP which was identified in the PVT bomb. That evidences that in this pressure interval gravitational force starts to lead the retrograde condensation progress.

The properties of colloidal solutions are intimately linked to the high surface area of the dispersed phase, as well as to the chemical nature of the particle's surface. How it can happen, we can see from simple physics. Three fundamental forces operate on fine particles in solution: 1) a gravitational force, tending to settle or raise particles depending on their density relative to the solvent; 2) a viscous drag force, which arises as a resistance to motion, since the fluid has to be forced apart as the particle moves through it; 3) the 'natural' kinetic energy of particles and molecules, which causes Brownian motion (Pashley, Karaman, 2004). However, the situation can change dramatically if colloidal substance is located in very tiny pores and directly contacts with large solid granular surfaces. Surface energy and force between granular surface and dispersed phase leads to the adsorption process.

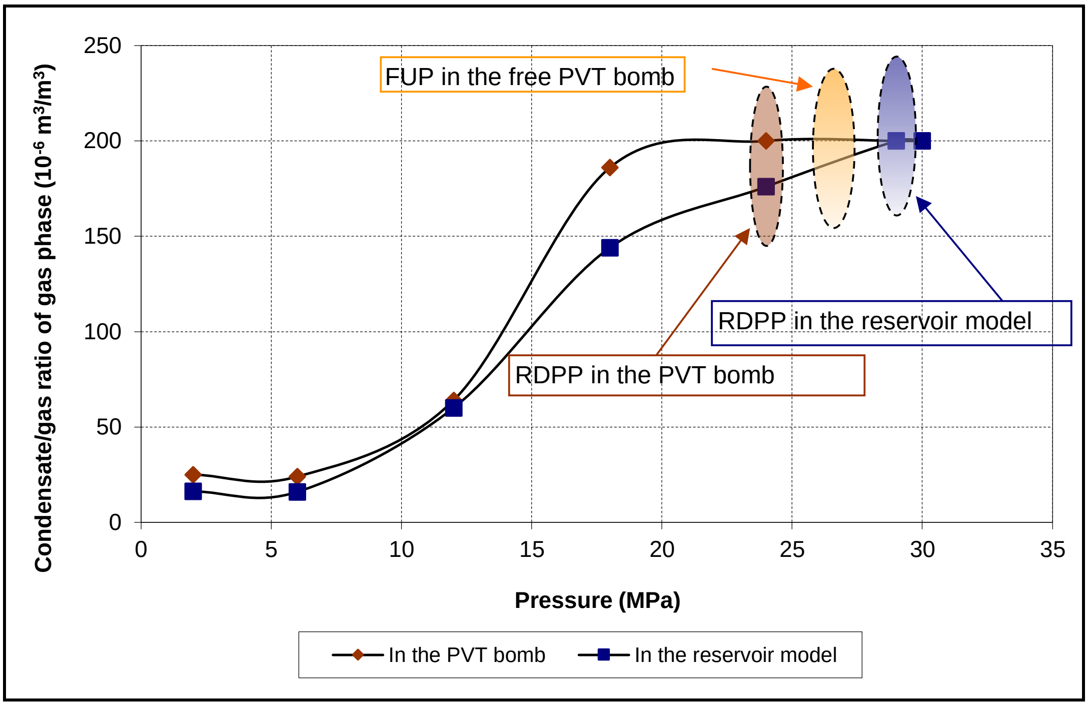

Figure 2. Differential condensation isotherms of gas-condensate fluid at temperature of 100 deg. C in the free PVT bomb and reservoir model.

Exactly this adsorption process between sub-micron-sized condensate particles and formation rock granular surfaces in the porous media causes early condensation when even gas-condensate system is above FUP which is identified in the PVT bomb. This will progress until then porous media saturated with hydrocarbon condensate. If pressure continuously depletes, then the condensate particles grow larger. When pressure is around RDPP (identified in the PVT cell) region the gravitation force will dominate the process and at some stage, break off the Brownian motion and will correspond to the maximum weight of the drop that can hang in the dispersion medium which is gas. That is reason why retrograde condensation was accelerated at this pressure point in the fig. 2. Also vertical filtration can occur due to gravity force being larger than the surface force in the reservoir condition at some stage when pressure is around or below RDPP (which was identified in the PVT bomb). However, this conclusion is obtained as the results of the experimental and theoretical studies. There is a need this conclusion to be tested in real reservoir condition because of some toleration on the modeling of formation condition and reservoir depletion process.

For this purpose, we analyzed the performance of a couple of wells on “Bulla-deniz” gas-condensate field. These wells are first drilled wells and that is why we could get some relevant information about formation flow characteristics in the downhole zone of the wells at early stage of field development. Well No20 average daily condensate/gas ratio per month in first two years was presented in the work (Abbasov, Fataliyev, 2015). For more detailed analyses, we included well No25 information as well (fig. 3).

Well No20 was drilled in April 1976, depth is 5443 m. Well No25 was drilled in June 1977, depth is 5757 m. Both wells belong to horizon VII which initial reservoir pressure – 71MPa, reservoir temperature –102^0C and condensate density – 800kg/m^3 were determined. Retrograde dew point pressure obtained 62.5MPa in the УГК-4 type of PVT bomb as per thermodynamic analyses on well No20 in 1976 (Abasov et al., 2013).

As it is shown in the fig. 3 condensate/gas ratio was increasing in the first 5 months since the well No20 started. In this period of time the factor even exceeded the condensate/gas ratio of this reservoir which was 362 g/m^3. It evidences that, two phases were flowing to the well in this period of time however reservoir pressure (71MPa) was above the retrograde dew point pressure (62.5MPa). It can be assumed that this was just stabilization period after drilling. There is a visible decrease over the next few months but then this continues in a cyclic trend. Same cyclic trend is presented for well No25 however during this time, reservoir pressure (65Mpa) was still above the fluid RDPP.

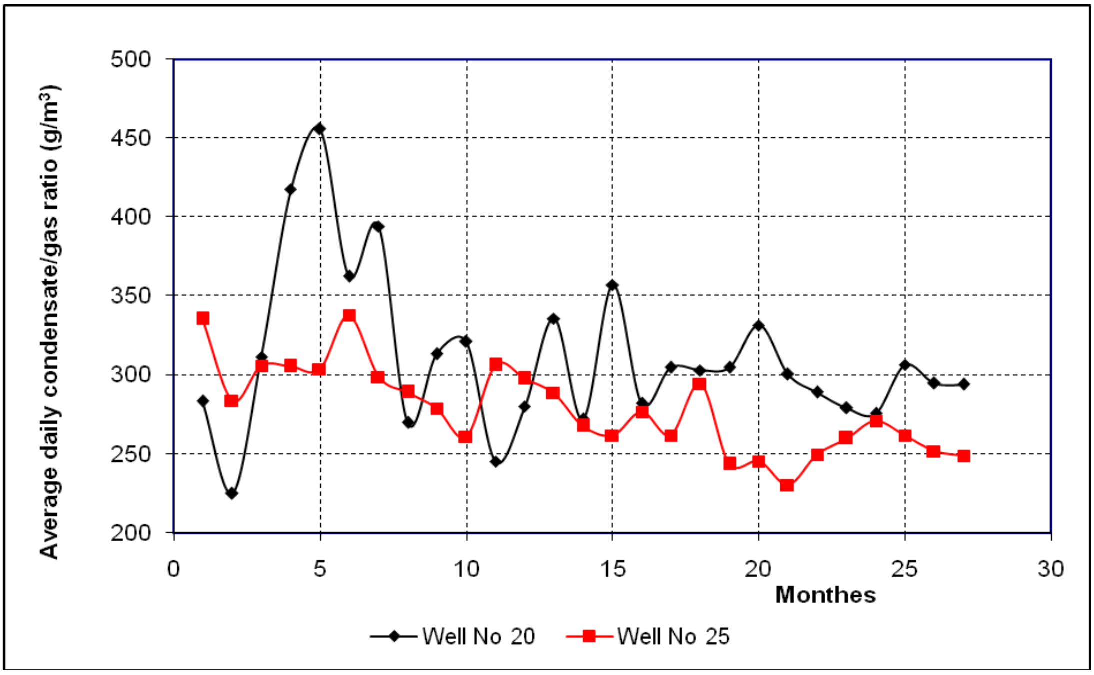

Figure 3. Average daily condensate/gas ratio characteristic of well No20 and No25 in first two years on "Bulla-deniz" gas-condensate field of Azerbaijan.

Reason for this phenomenon was explained that there are free condensate pools existing at some areas in the reservoir. These condensate pools can take part in the hydrodynamic processes and flow to the well under pressure gradient (Mirzadzhanzade et al., 2003). This explanation can answer some questions but it is well known that the field has been forming for many years under the influence of gravity. In this circumstance it looks unlikely that moveable condensate pools to be exist in some areas of the single gas phase region of the reservoir. Taking into account the results obtained above, we tried to explain the route differently.

At the time of discovery, a typical gas-condensate reservoir pressure might be above or close to the retrograde dew point pressure. If reservoir pressure is above system RDPP, then at this time there only single-phase gas exists. However, as the production is carried out, there is isothermal pressure decline and as the downhole pressure in a flowing well falls below a certain point of reservoir pressure which can be higher than FUP a liquid hydrocarbon phase is formed. In other words retrograde condensation starts at an earlier stage because of surface forces between sub-micron-sized condensate particles in the dispersed phase with formation rock granules. This condensate formation results in buildup of a liquid phase around the downhole, leading to a decrease in the effective permeability to gas into the wellbore. The productivity loss associated with condensate buildup can be substantial. The liquid dropout first occurs near the wellbore and propagates radially away from the well along with the pressure drop. Closer to the well, in the vicinity of the downhole where the liquid saturation reaches a critical value and the effluent travels as two-phase flow under pressure gradient. That repeats from time to time, so downhole zone washes periodically.

Conclusion

The colloidal feature of the gas-condensate system was investigated base on group of gas-condensate samples from Azerbaijan gas-condensate field "Bulla-deniz". It was confirmed that gas-condensate fluid is in dispersed condition when pressure is above the retrograde dew point pressure. If pressure decreases at a constant temperature, surface energy of dispersed phase increases and creates an environment for coalescing fine condensate particles. These sub-micron-sized particles grow following pressure drop and turns into aerosol-colloidal state which can be seen as the fogging up process. This transition pressure is defined as a fog up pressure-FUP. Also, confirmed that increasing the deference between FUP and RDPP with the increase of temperature can be considered well-matched with the properties of colloidal systems.

Furthermore, detailed analyses of experimental and theoretical studies, it was concluded that the surface energy and force between granular and dispersed phase surfaces leads to the adsorption process. Exactly this adsorption process between sub-micron-sized condensate particles and formation rock granular causes early condensation when even gas-condensate system is above FUP which is identified in the PVT bomb. This means that, if these factors are not analyzed or studied correctly at the beginning of the field development sooner or later production performance can suffer

This phenomenon was verified in real situation. For that, the flow behavior of the couple of wells on "Bulla-deniz" gas-condensate field was examined. Reason for flowing two phases when even reservoir pressure is above fluid retrograde dew point pressure stated differently using basic knowledge about colloidal substances

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