

# SIMULATION OF OFFLOADING OPERATIONS IN FPSO UNITS

**Alexandre Teixeira de Pinho Alho, D.Sc.**

Department of Naval & Ocean Engineering  
Federal University of Rio de Janeiro  
Centro de Tecnologia, Bl. C-203, Ilha do Fundão  
CEP 21945-970, Rio de Janeiro, RJ, Brazil  
e-mail: [alho@peno.coppe.ufrj.br](mailto:alho@peno.coppe.ufrj.br)

*Abstract. Complexes pipe networks are commonly encountered in marine installations on both ships and offshore plants. Today, the increasing demand on reducing plant costs emphasizes the economic advantage afforded by an efficient design. In this paper, the author presents the analysis of the offloading operation of a typical FPSO unit. The author adopted a new method to the analysis of pipe networks that seems to be most appealing when one has to deal with the analysis of fully branched systems. In this method, the network topology is described using a more straightforward approach based on a subsystem representation. The results obtained indicate that the application of pipe network analysis methods to the evaluation of the offloading process of a FPSO unit is a useful tool both at the design stage and during site operation.*

*Keywords. fluid, networks, design.*

## 1. Introduction

Complexes pumping systems are commonly encountered in marine installations on both ships and offshore plants. Similarly to industrial installations, the design of marine pumping systems consists essentially in the definition of pump and pipe network characteristics that must adhere to certain flow rate and pressure specifications. Traditionally, the design methodology of pumping systems consists of an iterative process, in which the characteristics of the system are defined using as reference recommended flow velocities, cost factors and system constrains. In order to obtain a workable design, this process must be repeated until the design requirements are satisfied.

Today, the increasing demand on reducing plant costs emphasizes the economic advantage afforded by an efficient design. One can conclude that this trial and error process may be efficient to a simple here-to-there pipe, but its application to the design of complexes systems with different operational configurations, such as the cargo systems of tanker ships, is virtually impracticable. In this sense, the cargo offloading system of a FPSO – *Floating, Production, Storage and Offloading* unit, is of particular interest due to stringent operational requirements and the differences in cargo piping layout in relation to conventional tankers. In addition to the structural requirements, the offloading operation of a FPSO unit should also satisfy rigorous requirements related to the dynamic behavior of the vessel.

In past decades, a great deal of research has been conducted on optimally design and operate pumping and piping systems. Several methods for the analysis of complex pipe networks have been proposed. In the majority of the methods proposed, the problem is solved by obtaining a flow distribution which satisfies flow continuity at each pipe junction and conservation of energy around any closed loop of pipes. Despite the large number of algorithms that have been developed for pipe network design, none of these procedures has been widely accepted or is being widely applied in the marine industry. This is partly due to the complexity of the techniques required to apply the algorithms to the analysis of systems with a high number of branched elements, as commonly encountered in marine installations.

In this work, the author presents the analysis of the offloading operation of a typical FPSO unit. The analysis comprehends the simulation of the operation of the cargo system during the offloading process. The author adopted a new method to the analysis of pipe networks that seems to be most appealing when one has to deal with the analysis of fully branched systems. In this method, the network topology is described using a more straightforward approach based on a subsystem representation. The results obtained indicate that the application of pipe network analysis methods to the evaluation of the offloading process of a FPSO unit is a useful tool both at the design stage and during site operation.

## 2. Historical Background

The first methods for solving pipe network problems were published by Hardy Cross in 1936. In his original paper, Cross proposes two different methods for the solution of pipe networks. In the first method, the basic hydraulics equations have been written in terms of the unknown flow rates in the pipes, which have been normally denoted as loop equations. Alternately, the basic hydraulics equations have been expressed in terms of unknown heads at junctions throughout the pipe system, which are usually referred to as node equations.

The Hardy Cross methods became the most extensively used methods. Of the two methods described by Hardy Cross, the method based on loop equations became the most widely used even today and is commonly denoted as the Hardy Cross method. However, convergence problems using Hardy Cross methods were recognized. Some authors suggested that the reason for the convergence problems is the fact that in both loop and node equations methods adjustments are computed independently of each other, with the result that convergence was often slow or non-existent in some cases. This fact, in conjunction with the significant advances in computing and programming facilities, has triggered the search for more efficient solving techniques.

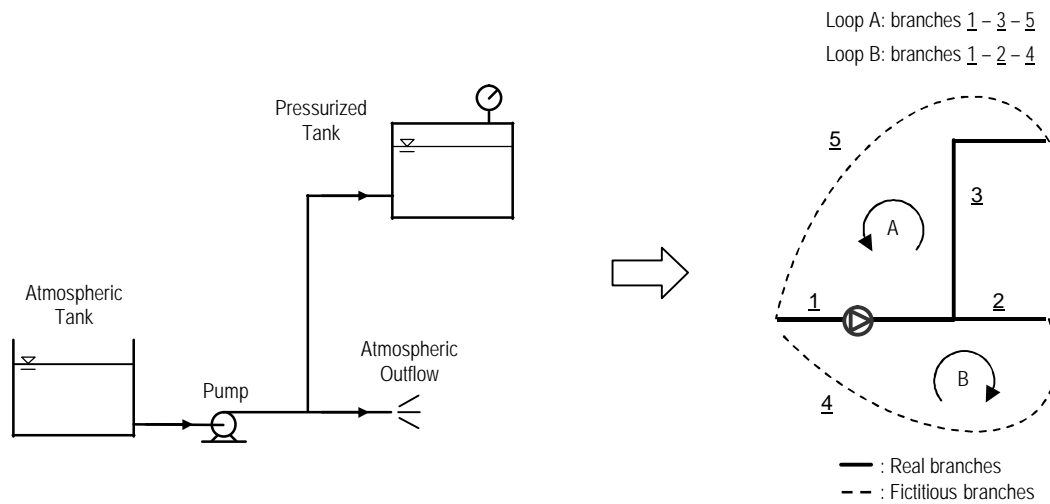


Figure 1. Example of system modeling using fictitious branches.

In this sense, Martin and Peters (1963) and Epp and Fowler (1970) proposed new procedures to simultaneously compute the adjustments for closed loop systems. The procedures had much improved convergence characteristics and become the basis for more general applications. The authors modified the Hardy Cross approach by using the Newton-Raphson technique for solving both loop and node equations, which was a significant improvement. This new approach lead to faster convergence and since then this technique has been widely accepted. Wood and Rayes (1981) conducted an extensive evaluation of the reliability of node oriented and loop oriented methods. The authors concluded that the loop oriented methods are more reliable than the node oriented methods. Nielsen (1989) developed an evaluation of the existing pipe networks analysis methods and showed that the choice of the model for the system of equations has a great influence on the behavior of the iterative process of solution. In his article, it is demonstrated that the problem formulation based on flow equations is better than the one based on node equations.

Regardless of the large number of algorithms that have been developed for pipe network analysis, none of these procedures has been widely adopted for the design of marine systems. The well-known convergence problems seem to be the main reason for the lack of interest in applying the node methods to the analysis of marine installations. As well, despite of their higher convergence efficiency, the loop methods do not have full acceptance in the marine industry. This is partly due to the complexity in applying the loop algorithms to the analysis of systems with a high number of branched elements, as commonly encountered in marine installations. The application of loop methods to the analysis of branched systems requires the introduction of fictitious branches to the original pipe network, as illustrated in Fig. (1). The basic idea of the fictitious branch method is to set up a network equivalent to the original system by making some special assumptions. Then, the equivalent network can be solved by conventional loop algorithms. It is easy to conclude that this approach is not an efficient alternative to the analysis of large branched systems.

In order to solve the problem of the analysis of fully branched systems more efficiently, the author adopted a new method based on a more straightforward approach. The adopted method is based on modeling the pipe network as a set of simultaneous subsystems (Alho, 2001). Similarly to the standard loop and nodal methods, the problem formulation with the subsystem approach comprehends a set of hydraulic equations expressed in terms of design parameters. By solving these set of simultaneous equations, the distribution of flow rates and pressures throughout the system is obtained. The subsystem method represents a more conceptually useful approach for marine applications and can be applied for both design and steady-state analysis of different operational conditions.

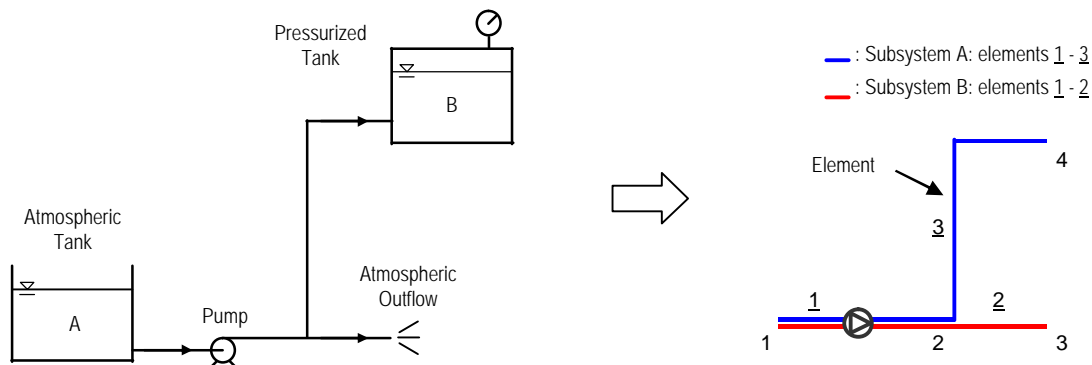


Figure 1. Example of subsystem representation.

## 2.1. Subsystem Formulation

The subsystem method is based on the modeling of a pipe network as a set of subsystems. A subsystem is formed by a set of pipes, or elements, that connects an inflow node to an outflow node of the network as illustrated in the Fig. (2). A node, or junction, represents the endpoints of an element. As an example, the Subsystem A in the Fig. (2) is formed by the elements 1 and 2, and connects the inflow node 1 to the outflow node 4.

The analysis of pipe networks is based on the simultaneous application of the principles of mass conservation and energy conservation. For a given system configuration, the principle of the mass conservation establishes that the algebraic sum of the inflows and outflows at a node must be equal to zero:

$$\sum_{k=1}^K \mathbf{I}_{j,k} Q_k = 0 \quad (1)$$

where  $Q_k$  is the flow rate in the element  $k$  and  $\mathbf{I}_{j,k}$  is a constant that represents the incidence of the element  $k$  in relation to the node  $j$ . Considering a steady state flow of an incompressible fluid, the principle of energy conservation states that the energy balance,  $\mathbf{DE}$ , in a subsystem  $i$  is expressed by:

$$(\Delta E)_i = \sum_{k=1}^K \mathbf{a}_{i,k} (\Delta E)_k \quad ; \quad (\Delta E)_k = (\Delta P)_k + \mathbf{r}g(\Delta z)_k + \frac{1}{2} \mathbf{r}(\Delta V^2)_k + (\Delta l_T)_k - h_k = 0 \quad (2)$$

where  $P$  is the static pressure,  $z$  is the vertical height of a junction,  $V$  is the flow velocity,  $\mathbf{D}l_T$  is the total head loss and  $h$  is the energy added by a fan or a pump. In Eq. (2),  $\mathbf{r}$  represents the fluid density and  $g$  the acceleration of gravity. The term  $(\mathbf{DE})_k$  represents the energy balance in a single pipe element  $k$ . The coefficient  $\mathbf{a}_{i,k}$  is equal to unity if the pipe element  $k$  is one of the elements that forms the subsystem  $i$ . Otherwise,  $\mathbf{a}_{i,k}$  is equal to zero.

Considering the hypothesis of a turbulent flow, the total head loss load in each pipe element  $k$  can be expressed by:

$$(\Delta l_T)_k \cong C_{Dk} Q_k^m \quad (3)$$

where  $C_D$  represents the total head loss coefficient. The values of  $C_D$  and the exponent  $m$  are obtained by appropriate formulations, based on flow characteristics. For the case of flow of liquids, the total head loss can be estimated by Darcy-Weisbach formulation:

$$\Delta l_T = f \left( \frac{L + L_E}{D} \right) \frac{Q^2}{2gA_T^2} \quad (4)$$

where  $f$  represents the friction factor,  $L$  the length of the pipe,  $L_E$  the equivalent length of fittings and valves,  $D$  the internal diameter and  $A_T$  the sectional area of the pipe. A pipe element can be equipped with one or more pumps. The head supplied by the pump to the fluid can be appropriately represented by a function of the type:

$$h = \mathbf{f}(Q) \quad (5)$$

where the function  $\mathbf{f}(Q)$  and its respective coefficients can be determined from the performance curves of the pump.

Combining the equations of mass conservation, Eq. (1), with the equations of energy conservation, Eq. (2), it is obtained a system of equations, whose unknowns represent the flow rate in each pipe element  $k$ . The continuity relationships are linear algebraic equations while the relationships describing the conservation of energy in a subsystem are generally nonlinear algebraic equations and an iterative method for the simultaneous solution of the equations must be applied. In the present work, the Newton-Raphson technique was adopted for the solution of the system of equations.

The solution of the system of equations represents the flow rate distribution in the system for a given operation configuration. In systems equipped with pumps, the pump flow rate is given directly by the value of the corresponding pipe element. The operating point of the pump can be completely determined using Eq. (5) for the calculation of the pump head.

## 3. Case Studied

The system selected for this study was the cargo offloading system of a FPSO – *Floating, Production, Storage and Offloading* unit. The offloading operation in a FPSO unit consists in a cargo transfer procedure that is executed on a regular basis. During the offloading process, the oil stored in the FPSO tanks is transferred to the cargo tanks of another ship, usually called shuttle tanker. Since the offloading operation imposes significant effects on the weight distribution of the vessel, it must be planned in accordance to both structural and stability requirements.

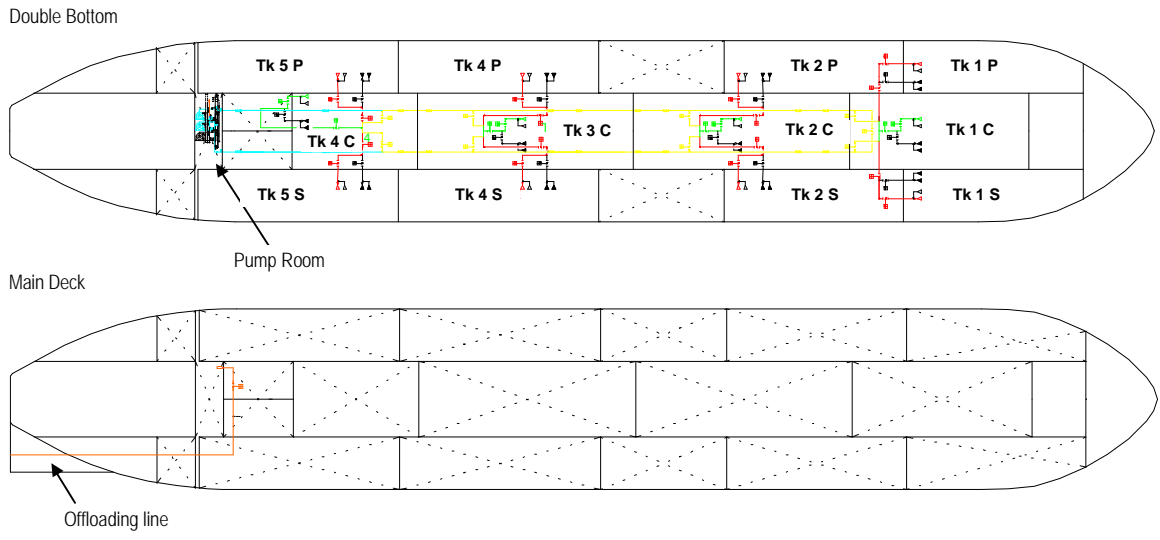


Figure 3. FPSO tank arrangement and cargo piping layout.

Table 1. FPSO main particulars.

|                |                        |
|----------------|------------------------|
| Length, bp     | 315,0 m                |
| Breadth        | 51,8 m                 |
| Depth          | 26,7 m                 |
| Draught        | 20,9 m                 |
| Cargo capacity | 270.000 m <sup>3</sup> |

Table 2. Offloading operation planning at design stage.

| Step | Tank - Flow Rate (m <sup>3</sup> /h) |      |      |      |      |      |      |      | Flow Rate |
|------|--------------------------------------|------|------|------|------|------|------|------|-----------|
|      | 1C                                   | 2C   | 3C   | 4C   | 1P/S | 2P/S | 4P/S | 5P/S |           |
| 1    | 0                                    | 0    | 0    | 0    | 1125 | 0    | 0    | 1125 | 4500      |
| 2    | 2250                                 | 0    | 0    | 2250 | 0    | 0    | 0    | 0    | 4500      |
| 3    | 0                                    | 2250 | 0    | 2250 | 0    | 0    | 0    | 0    | 4500      |
| 4    | 0                                    | 0    | 0    | 0    | 0    | 2250 | 0    | 0    | 4500      |
| 5    | 2250                                 | 0    | 0    | 2250 | 0    | 0    | 0    | 0    | 4500      |
| 6    | 0                                    | 2250 | 0    | 0    | 0    | 0    | 1125 | 0    | 4500      |
| 7    | 0                                    | 4500 | 0    | 0    | 0    | 0    | 0    | 0    | 4500      |
| 8    | 2250                                 | 0    | 0    | 2250 | 0    | 0    | 0    | 0    | 4500      |
| 9    | 4500                                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 4500      |
| 10   | 0                                    | 0    | 0    | 0    | 0    | 1125 | 0    | 1125 | 4500      |
| 11   | 4500                                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 4500      |
| 12   | 0                                    | 0    | 0    | 0    | 1125 | 0    | 1125 | 0    | 4500      |
| 13   | 0                                    | 0    | 0    | 0    | 1125 | 0    | 1125 | 0    | 4500      |
| 14   | 0                                    | 0    | 4500 | 0    | 0    | 0    | 0    | 0    | 4500      |
| 15   | 0                                    | 0    | 0    | 0    | 0    | 1125 | 1125 | 0    | 4500      |
| 16   | 0                                    | 0    | 0    | 0    | 1125 | 0    | 0    | 1125 | 4500      |
| 17   | 0                                    | 4500 | 0    | 0    | 0    | 0    | 0    | 0    | 4500      |
| 18   | 0                                    | 0    | 0    | 0    | 1125 | 0    | 0    | 1125 | 4500      |
| 19   | 0                                    | 0    | 4500 | 0    | 0    | 0    | 0    | 0    | 4500      |
| 20   | 0                                    | 0    | 0    | 4500 | 0    | 0    | 0    | 0    | 4500      |
| 21   | 0                                    | 0    | 2250 | 0    | 0    | 1125 | 0    | 0    | 4500      |
| 22   | 0                                    | 0    | 0    | 0    | 0    | 0    | 1125 | 1125 | 4500      |
| 23   | 0                                    | 0    | 4500 | 0    | 0    | 0    | 0    | 0    | 4500      |
| 24   | 0                                    | 2250 | 0    | 2250 | 0    | 0    | 0    | 0    | 4500      |

The cargo offloading system of a FPSO is of particular interest due to rigorous operational requirements and the differences in cargo piping layout in relation to conventional tankers. In addition to the structural and static stability requirements, the offloading operation of a FPSO unit should satisfy rigorous requirements related to the dynamic behavior of the vessel. Such requirements are related to the dynamic stability of the ship and the maximum loads that can be applied to her mooring system and the risers that bring the oil from the production wells. Another particular feature of the FPSO units is that the cargo offloading is made through a single discharge line to the shuttle tanker. This characteristic imposes a restriction to the offloading flow rate value, since the maximum flow rate is limited by the maximum flow velocity allowed in the main discharge line. This stringent restriction is not observed in conventional tanker ships since every cargo pump has its own discharge line.

As a reference for the study, a typical FPSO unit operating in Campos Basin, Brazil, was adopted. It consists of an existing VLCC ship that was converted into a FPSO unit. Its main particulars are shown in Tab. (1). The ship has of 15 tanks, but only 12 tanks are used to store the oil produced (Fig. 3). The remainder tanks are used as segregated ballast tanks. The total volume offloaded from the ship represents approximately 80% of the total cargo tank capacity. The original planning of the offloading operation in study is presented in Tab. (2). The operation is divided in 24 steps, each one with 2 hours of duration. It was assumed to each step a constant flow rate of 4500 m<sup>3</sup>/h. The offloading sequence shown in Tab. (2) was developed at design stage based only on structural and static stability requirements.

The pipe network of the cargo system was designed with a mixed configuration. There are two 30 in main pipes installed in a loop arrangement, as illustrated in Fig. (3). The cargo tanks are connected to the main pipes by 18 in pipe branches. Independent control/blockage valves can adjust the flow rate of each cargo tank. The single offloading line on main deck has a nominal diameter of 36 in. The system is equipped with three centrifugal cargo pumps. During normal operating conditions, two pumps are in service, while the third one stays in stand-by mode. At the operating point, each cargo pump is rated at 4500 m<sup>3</sup>/h with a total discharge head of 32 m, at a constant speed of 885 rpm (design point).

#### 4. Simulation of the Offloading Operation

The design of a FPSO offloading system can involve several distinct problems. One of them, which usually requires a great effort, relates to its functioning, that means meeting flow rate requirements. To carry out this task, it is necessary to determine the flow rate distribution of the system in each offloading step. Then, the operation of the system can be evaluated comparing the calculated flow rate distribution with that established in the original planning.

The flow rate distribution in each offloading step can be determined by a steady-state simulation of the operation of the system. In order to solve the problem of the steady-state simulation more efficiently, the offloading system was modeled as a set of simultaneous subsystems, in that each subsystem represents the set of pipe elements that connects a cargo tank to the system manifold. Considering this approach, a specific model was generated for each offloading step. These models include the representation of the cargo tanks, the pipe elements and the pumps in operation.

An example of a subsystem model developed for the simulation of the offloading operation is shown in Fig. (4). The model shown in Fig. (4) represents the subsystem model of the step 6 of the offloading operation. As can be seen from Tab. (2), only tanks 2C, 4P and 4S are in operation during step 6. From Fig. (3), it is possible to verify that the side tanks 4P and 4S are in parallel operation. The associated discharge from tanks 4P and 4S are also in parallel operation with the discharge from tank 2C.

This example illustrates the efficiency of the subsystem approach for modeling branched systems. In the subsystem method, the topological information of the real system is fully transcribed to the subsystem model. This feature represents an important advantage when dealing with large branched systems in which loop methods require the introduction of a great number of fictitious branches to the original pipe network.

In order to facilitate system analysis process, the subsystem algorithm was implemented in a computer program called *PNA – Pipe Network Analyzer*, developed by the author at the Department of Naval & Ocean Engineering, Rio de Janeiro Federal University. The software is basically a pipe network solver based on the subsystem approach. The results of the simulations of each step of the offloading operation are presented in Tab. (3).

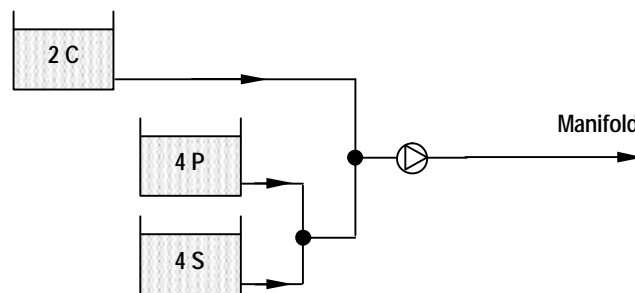


Figure 4. System model for the step 6 of the offloading operation.

Table 3. Operation analysis results.

| . Operation Analysis    |      |      |      |      |       |       |      |       |           | Flow Rate Distribution |        |  |
|-------------------------|------|------|------|------|-------|-------|------|-------|-----------|------------------------|--------|--|
| Tank - Flow Rate (m³/h) |      |      |      |      |       |       |      |       |           |                        |        |  |
| Step                    | 1C   | 2C   | 3C   | 4C   | 1P/S  | 2P/S  | 4P/S | 5P/S  | Flow Rate | Pump Head              | Dif.   |  |
| 1                       | 0    | 0    | 0    | 0    | 1268  | 0     | 0    | 1519  | 5574      | 23,6                   | 23,9%  |  |
| 2                       | 2603 | 0    | 0    | 2961 | 0     | 0     | 0    | 0     | 5564      | 23,7                   | 23,6%  |  |
| 3                       | 0    | 3142 | 0    | 2280 | 0     | 0     | 0    | 0     | 5422      | 25,1                   | 20,5%  |  |
| 4                       | 0    | 0    | 0    | 0    | 0     | 2616  | 0    | 0     | 5232      | 26,8                   | 16,3%  |  |
| 5                       | 2956 | 0    | 0    | 2168 | 0     | 0     | 0    | 0     | 5124      | 27,7                   | 13,9%  |  |
| 6                       | 0    | 1153 | 0    | 0    | 0     | 0     | 2290 | 0     | 5733      | 22,0                   | 27,4%  |  |
| 7                       | 0    | 4115 | 0    | 0    | 0     | 0     | 0    | 0     | 4115      | 34,1                   | -8,6%  |  |
| 8                       | 2868 | 0    | 0    | 2009 | 0     | 0     | 0    | 0     | 4877      | 29,6                   | 8,4%   |  |
| 9                       | 3667 | 0    | 0    | 0    | 0     | 0     | 0    | 0     | 3667      | 35,7                   | -18,5% |  |
| 10                      | 0    | 0    | 0    | 0    | 0     | ----- | 0    | ----- | -----     | -----                  | -----  |  |
| 11                      | 2592 | 0    | 0    | 0    | 0     | 0     | 0    | 0     | 2592      | 39,5                   | -42,4% |  |
| 12                      | 0    | 0    | 0    | 0    | 1183  | 0     | 1417 | 0     | 5200      | 27,1                   | 15,6%  |  |
| 13                      | 0    | 0    | 0    | 0    | 1307  | 0     | 1566 | 0     | 5746      | 21,9                   | 27,7%  |  |
| 14                      | 0    | 0    | 5473 | 0    | 0     | 0     | 0    | 0     | 5473      | 25,5                   | 21,6%  |  |
| 15                      | 0    | 0    | 0    | 0    | 0     | 1072  | 1234 | 0     | 4612      | 31,4                   | 2,5%   |  |
| 16                      | 0    | 0    | 0    | 0    | ----- | 0     | 0    | ----- | -----     | -----                  | -----  |  |
| 17                      | 0    | 3935 | 0    | 0    | 0     | 0     | 0    | 0     | 3935      | 35,0                   | -12,6% |  |
| 18                      | 0    | 0    | 0    | 0    | ----- | 0     | 0    | ----- | -----     | -----                  | -----  |  |
| 19                      | 0    | 0    | 5227 | 0    | 0     | 0     | 0    | 0     | 5227      | 27,3                   | 16,2%  |  |
| 20                      | 0    | 0    | 0    | 4307 | 0     | 0     | 0    | 0     | 4307      | 33,1                   | -4,3%  |  |
| 21                      | 0    | 0    | 4214 | 0    | 0     | 252   | 0    | 0     | 4718      | 30,8                   | 4,8%   |  |
| 22                      | 0    | 0    | 0    | 0    | 0     | 0     | 1087 | 1145  | 4464      | 32,3                   | -0,8%  |  |
| 23                      | 0    | 0    | 4241 | 0    | 0     | 0     | 0    | 0     | 4241      | 33,5                   | -5,8%  |  |
| 24                      | 0    | 2110 | 0    | 2307 | 0     | 0     | 0    | 0     | 4417      | 32,6                   | -1,8%  |  |

Table 4. Flow distribution after pressure adjustments.

| . Operation Analysis    |      |      |      |      |      |      |      |      |           | Flow adjustments by valve stroking |        |  |
|-------------------------|------|------|------|------|------|------|------|------|-----------|------------------------------------|--------|--|
| Tank - Flow Rate (m³/h) |      |      |      |      |      |      |      |      |           |                                    |        |  |
| Step                    | 1C   | 2C   | 3C   | 4C   | 1P/S | 2P/S | 4P/S | 5P/S | Flow Rate | Pump Head                          | Dif.   |  |
| 1                       | 0    | 0    | 0    | 0    | 1268 | 0    | 0    | 1519 | 5574      | 23,6                               | 23,9%  |  |
| 2                       | 2603 | 0    | 0    | 2961 | 0    | 0    | 0    | 0    | 5564      | 23,7                               | 23,6%  |  |
| 3                       | 0    | 3142 | 0    | 2280 | 0    | 0    | 0    | 0    | 5422      | 25,1                               | 20,5%  |  |
| 4                       | 0    | 0    | 0    | 0    | 0    | 2616 | 0    | 0    | 5232      | 26,8                               | 16,3%  |  |
| 5                       | 2956 | 0    | 0    | 2168 | 0    | 0    | 0    | 0    | 5124      | 27,7                               | 13,9%  |  |
| 6                       | 0    | 2253 | 0    | 0    | 0    | 0    | 1669 | 0    | 5591      | 23,5                               | 24,2%  |  |
| 7                       | 0    | 4115 | 0    | 0    | 0    | 0    | 0    | 0    | 4115      | 34,1                               | -8,6%  |  |
| 8                       | 2868 | 0    | 0    | 2009 | 0    | 0    | 0    | 0    | 4877      | 29,6                               | 8,4%   |  |
| 9                       | 3667 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 3667      | 35,7                               | -18,5% |  |
| 10                      | 0    | 0    | 0    | 0    | 0    | 1275 | 0    | 1275 | 5100      | 27,9                               | 13,3%  |  |
| 11                      | 2592 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 2592      | 39,5                               | -42,4% |  |
| 12                      | 0    | 0    | 0    | 0    | 1183 | 0    | 1417 | 0    | 5200      | 27,1                               | 15,6%  |  |
| 13                      | 0    | 0    | 0    | 0    | 1307 | 0    | 1566 | 0    | 5746      | 21,9                               | 27,7%  |  |
| 14                      | 0    | 0    | 5473 | 0    | 0    | 0    | 0    | 0    | 5473      | 25,5                               | 21,6%  |  |
| 15                      | 0    | 0    | 0    | 0    | 0    | 1072 | 1234 | 0    | 4612      | 31,4                               | 2,5%   |  |
| 16                      | 0    | 0    | 0    | 0    | 1230 | 0    | 0    | 1230 | 4920      | 29,3                               | 9,3%   |  |
| 17                      | 0    | 3935 | 0    | 0    | 0    | 0    | 0    | 0    | 3935      | 35,0                               | -12,6% |  |
| 18                      | 0    | 0    | 0    | 0    | 1058 | 0    | 0    | 1058 | 4232      | 33,6                               | -6,0%  |  |
| 19                      | 0    | 0    | 5227 | 0    | 0    | 0    | 0    | 0    | 5227      | 27,3                               | 16,2%  |  |
| 20                      | 0    | 0    | 0    | 4307 | 0    | 0    | 0    | 0    | 4307      | 33,1                               | -4,3%  |  |
| 21                      | 0    | 0    | 2249 | 0    | 0    | 1170 | 0    | 0    | 4589      | 31,6                               | 2,0%   |  |
| 22                      | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 2151 | 4302      | 33,2                               | -4,4%  |  |
| 23                      | 0    | 0    | 4241 | 0    | 0    | 0    | 0    | 0    | 4241      | 33,5                               | -5,8%  |  |
| 24                      | 0    | 2110 | 0    | 2307 | 0    | 0    | 0    | 0    | 4417      | 32,6                               | -1,8%  |  |

## 5. Results Analysis

The simulations showed some interesting results. As expected, the flow rates observed at the beginning of the offloading operation are higher than that verified at the final steps. This effect results from the variation of the static head corresponding to the variation of the cargo level inside the tanks of the FPSO and the shuttle tanker. This effect is somewhat minimized by the variation of the draught of both ships during the operation. In this case, the draught of FPSO is reduced progressively while the draught of the shuttle tanker increases.

Another expected result is that the larger the distance between the tank and the pump room, the lower the operation flow rate. When this effect is combined with a low liquid level, the influence on the flow rate is very expressive, as can be seen in step 21 (Tab. 3). This effect can be so adverse that the operation cannot be executed. This is the case in steps 10, 16 and 18. The parallel operation of the cargo tanks in these steps is not possible because the combined effect of a low static pressure and a high head loss.

This indicates that the pressures in the system should be balanced so that such operation can be executed. A simple solution for this problem is to control the flow rate of each tank by valve stroking. Based on this procedure, the flow rates of the tanks in service in steps 6, 10, 16, 18 and 21 were balanced. The results obtained are presented in the Tab. (4). The analysis of the volume transferred from each tank allowed to conclude that the operation of the tanks 4P/S is finished in the step 15, and not in the step 22, as initially established in the offloading planning.

The effect of the low static pressure can also be noted in the steps that there is just one tank in operation. This is the case of the steps 9 and 11, in which low values of flow rate are observed. In these cases, an alternative was analyzed based on the operation in parallel of two cargo pumps. However, the analysis of this operation showed that the flow rate increases only 139 m<sup>3</sup>/h and 399 m<sup>3</sup>/h in steps 9 and 11, respectively. The magnitude of the calculated variations in the flow rates may not justify the extra power demanded by the parallel operation of the cargo pumps.

In Fig. (5), the operating points of the cargo pumps during the offloading operation are plotted. It can be observed a balanced distribution of the actual operating points around the design operating points. During the offloading operation, the pump power varies from 464 HP to 535 HP.

The analysis of the results indicates the need to apply some adjustments in the system to guarantee the execution of the offloading operation. The calculation of the time length of each step, now based on more realistic flow rate values, indicated that it is possible to execute the offloading operation with the duration originally established. However, it is important to emphasize that the adjustment of the system was executed through the control of the flow rate by valve stroking, what represents a loss of energy. With a simulation tool, it is possible to develop an optimization process of the offloading operation seeking to minimize the use of such alternative. In the case of new designs, it could also be optimized the selection of the cargo pumps and the piping system itself.

## 6. Conclusions

In this work, the author presents the simulation of the offloading operation of a typical FPSO unit. The analysis of the operation showed significant discrepancies between the calculated flow distribution and the one established in the original offloading planning. In addition, the evaluation indicated the need to apply some adjustments in the system to guarantee the execution of the process. These results showed that pipe network analysis methods represent a useful tool to evaluate the operation of the offloading system of FPSO units.

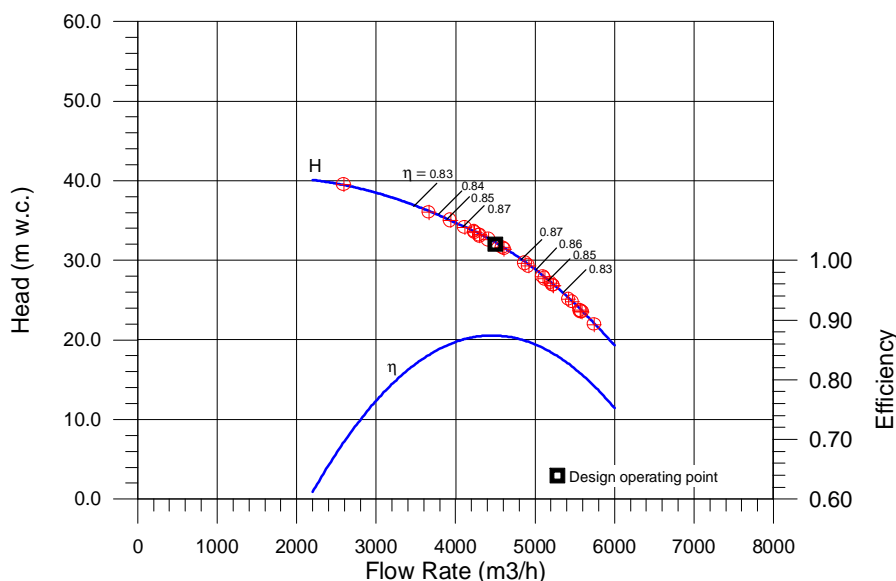


Figure 5. Cargo pump performance curves.

The results showed also that the subsystem method is effective for the analysis of complexes branched networks. In this sense, the method is conceptually useful for marine applications. Although the method was only applied in this work to the analysis of the operation of a pumping system at design stage, further potential exists for improvement and extension of its capabilities. For example, along the time, the systems may be subjected to modifications, such as the replacement of equipments and the implementation of new operational requirements. The subsystem method can be used to the development of an efficient simulation tool that allows the analysis of future operational conditions, given the designer a chance to foresee the potential effects in the operation of the system. Besides this, the resources offered by a simulation tool with such characteristics can be also used for the training of the system operators.

## 7. References

- Alho, A. T. P., "Pipe Network Analysis based on a Subsystem Modeling", Proceedings of the 3rd Brazilian Pipeline Conference, Rio de Janeiro, Brazil (2001). (*In Portuguese*).
- Epp, R. and Fowler, A. G., "Efficient Code for Steady-State Flows in Networks", *Journal of the Hydraulics Division*, Proceedings of the ASCE, Vol. 96, No. HY1, January (1970), pp. 43-56.
- Larock, B. E., Jeppson, R. W. and Watters, G. Z., *Hydraulics of Pipeline Systems*. Boca Raton-FA, USA, CRC Press, (2000).
- Martin, D. W. and Peters, G., "The Application of Newton's Method of Network Analysis by Digital Computer", *Journal of the institute of Water Engineers*, Vol. 17, (1963), pp. 115-129.
- Nielsen, H. B., "Methods for Analyzing Pipe Networks", *Journal of Hydraulic Division*, Vol. 115, No. 2, February (1989), pp. 139-157.
- Wood, D. J. and Charles, C. O., "Hydraulic Network Analysis Using Linear Theory", *Journal of the Hydraulics Division*, Proceedings of the ASCE, Vol. 98, No. HY7, July (1972), pp. 1157-1170.
- Wood, D. J. and Rayes, A. G., "Reliability of Algorithms for Pipe Network Analysis", *Journal of the Hydraulics Division*, Proceedings of the ASCE, Vol. 107, No. HY10, October (1981) pp. 1145-1161.