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Explorative Computation on Vacuum-Energized Fluid Conveyance

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Abstract—**The vacuum-accumulated energy (VAE) computation presented in this paper models the fluctuation and characteristics of vacuum-energized pressure in a fluidic-conveying line. Based on the energy consumption of the fluidic conveyance, non-continuity, periodicity, the fluidic conveyance Switch-On (FCSO) process, vacuumed-energy consumption process, and vacuum recovery (VR) process are simultaneously considered by means of this method. Since the simulative computation model agrees with the experimental data, the present method is available in engineering applications.**

Index Terms—**Vacuum- accumulated energy, Conveyance switch-on process, Vacuumed-energy consumption**

I. Introduction

The first prototype of vacuum-powered fluidic conveyance (VPFC) system appeared years ago, but the relevant rationale, model and applications have been inadequate to successfully model the system. VPFC demonstrates advantages when compared to the technique of natural gravity and is more frequently applied in engineering [1-5], showing its positive effects on the economy and ecological environment. On the other hand, relevant experimentation reveals that the fill the pipe and is intermittent inflow. Thus the single-phase flow model and corresponding methods are not proper to describe properties of VPFC. Pressure declining calculation of continuous flow is also not suitable in most cases. In a residential district, the vacuum-powered fluidic conveyance system is comprised of many working modules, each having a small cell and major pipe，connected to the cell and imaginarily segmented in construction. In terms of vacuum pressure dynamics, an FCSO process goes on by sensing the liquid level in the small cell within a time-designated limit. The vacuum recovery process triggered on by sensing vacuum in the major pipe. Since the modules operate randomly, the major pipe works in a random sequence of FCSO and /or vacuum recovery processes.

In order to systematically perceive the regularity of VPFC, this paper puts forth some new concepts and established a precise model. Having considered the physical process of gaseous-and-liquid phases in VPFC and the pressure fluctuation of the VAE, it is sufficient that the present research approaches analysis of the VPFC, normalizes the random sequence, simulates the model, designs a network layout and develops algorithms and computations of VPFC. The present paper has set a necessary and solid foundation for engineering applications.

II. Process Characteristics of VAE in VPFC

Pipeline fluidic conveyance can be governed by the pressure-differential mechanism. In the mechanism, it is the fundamental and regular pattern to accumulate vacuum energy in minutes, but consume the accumulated energy in seconds. It is critical to maintain the powered vacuum at an indicated level in a module and sustain a cascade of segmented fluidic conveyances continued in a major pipe. A typical process of VAE pressure in fluidic conveyance is shown in Figure 1.

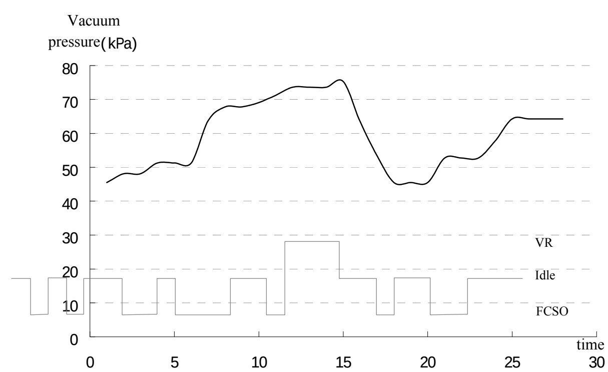

Figure.1 A Pressure Process of VAE in Fluidic Conveyance

During a process of vacuum powered fluidic conveyance, the fluctuated vacuum of VAE varies with VAE loss caused by the conveying of fluid and VAE supply provided by the vacuum pump in the major pipe. The dynamic process of VPFC is actually a series of on-or-off working modules. FCSO processes and VR processes are placed in a module. A FCSO process denotes a timed period of flowing operation of liquid from the cell into the segmented major pipe in a module and down the line under powered-vacuum. VAE consumption is part of the FCSO process so a VR process is required to increase the vacuum in

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the system to the designated level in the major pipe by means of vacuum generator(s). The required fluidic conveyance of a module carried out by this repetitive process. The fluidic conveyance in the major pipe is a cascade of individual modular, control of which is scattered along the line of major pipe. The fluidic conveyance in a major pipe is a combination of the segmented-major-pipe conveyances weighted variously**.** In an idle interval of time, the entire VPFC system is not activated at all.

The FCSO process of the major pipe line could be regarded as a sum of the modular FCSO processes. A normalized VPFC sequence comes by randomly combining the VR processes, FCSO processes and idle intervals shown as the rectangular curve in Figure 1. Therefore, a model can be developed to simulate the process.

III. VAE'S LOSS

Due to the characteristics of VAE it is not suggested to use differentiation in mathematics, but integration to address the applicable processes in fluidic conveyance. Such as modeling the relations between state variables and exploiting the model for further calculation from a stable-ended state to next. In application, the multi-group gases in a confined space frequently transit between different states. The results from analysis and calculation of this state transition provide the theoretical basis and the design scheme for engineering applications.

Given n groups of gas, 1, 2,…, n, are all constant, and comply with the gas state equation set, assuming an isothermal process for simplicity, the equilibrium pressure p_e over the constant multi-group gas system is obtained. Suppose the volume of gaseous group i is V_{i0}, and the fixed sum of volume in the major pipe is V_N, then the initial gas cubic ratio of V_{i0} over V_N is

$$k_i = \frac{V_{i0}}{V_N} \qquad i = 1,2,...,n \quad (1)$$

The equilibrium-state pressure equation from a set of n constant gaseous groups in uniform phase can be defined using the following equation:

$$p_e = \sum_{i=1}^{n} k_i p_{i0} \qquad (2)$$

Equation (2) is the general form, simplified from the ideal gas equation set. The equilibrium pressure comes in recognition of the contribution of the initial states of every partial gas. The resulted total vacuum pressure in the multi-group gas system is a weighted sum of the partial pressures. This equation is referred to as pressure-volume transition constant (PVTC) principle. The principle can be used for the analysis of VAE dynamics and is the key to analyzing the running model of fluidic conveyance of VAE in practical applications.

As mentioned above, the fluidic conveyance of a module is completed by a number of FCSO processes. Modeling the state transition process of the physical states in effect yields how much VAE is consumed for a single FCSO process or jointed FCSO processes by means of the PVTC principle. The liquid in the cell of a module is pushed into the vacuumed major pipeline, and an FCSO process is able to divide into a liquid and gaseous phases. When the major pipe is not in idle, its states, by running a FCSO process, is represented with a series of running modules, of which the gaseous phases are all in the terminal states. The primary focus of this paper is on the ended state of the system.

Prior to an FCSO process in a module, the switch is off, and the vacuum system is in standby. The initial pressure of the major pipe is p_-, and the initial pressure in the cell is p_+. The volume of the major pipeline, volumes of the gas and the liquid of the cell are V_N, V_g and V_l respectively. After the FCSO process starts, atmospheric pressure acts as an imaginary piston-like interface that drives the liquid in the cell into the major pipe. Even though gases are released and dissolved into the liquid, this stage of the FCSO process is primarily liquid flow, defined as the liquid phase or the former part of the FCSO process. The terminal pressure of the liquid phase arrives at p_l. Because of the residual pressure from the exterior p_+, the piston-like imaginary interface drives the remaining gas of the cell into that segmented major pipeline. The stage of the FCSO process, characterized by flowing gas is defined as gas phase or the latter part of the FCSO process. Turning the switch off ends the gas phase, but the piston interface effect does not stop until the gaseous volume expanded from V_g into V_N-V_l and the pressure in the major pipe gradually rises up to equilibrium p_e .

IV. VAE LOSS IN A GAS PHASE

The gaseous phase of an FCSO process propels the liquid sucked in the major pipe during the liquid phase, and is the primary consumer of VAE. Apart from minor the VAE consumption during the liquid phase, a further simplified operational model is shown as figure 2, and are able to use in engineering

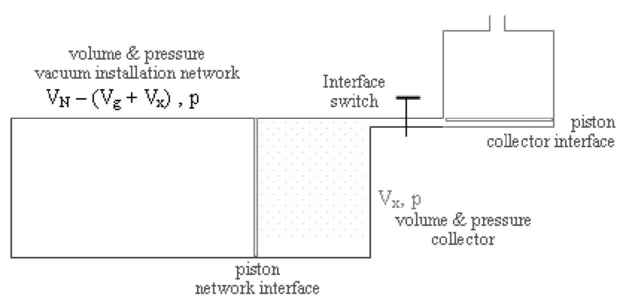

Figure.2 State of Gas Phase of FCSO Process

According to the PVTC principle and operational model in Figure 2, the associated gas state equations for the segmented major pipeline in a time of FCSO process is:

$$V_N p_- = (V_N – V_x) p_e \qquad (3a)$$

$$V_g p_+ = V_x p_e \qquad (3b)$$

Where the left terms of equations (3a, b) are the states of the two groups of gas before the FCSO process and the right terms are after. V_N is the volume of the major pipe, in which p_-, the designated pressure in vacuum; at a time of FCSO process, V_g is the volume of gas pulled from the cell of a module, where p_+ is the driving (barometric) pressure and V_x is the equilibrium volume of the gas at pressure p_e. Meanwhile, the equilibrium pressure can be derived as follows.

$$p_e = k_N p_- + k_g p_+ \qquad (4)$$

Where k_N is the initial gaseous-cubic ratio of the major pipeline, and k_g is of the cell. In engineering, k_N is fixed, and k_g adjustable as defined below:

$$k_N = 1 \qquad (5a)$$

$$k_g = \frac{V_g}{V_N} \qquad (5b)$$

Under the definite gaseous-cubic ratio, (k_N - k_g) indicates the capability the major pipeline to sustain VAE, referred to here as the vacuum-accumulated index. k_g this number reflects the capability of the sucked-in gas in the cell to consume VAE in fluidic conveyance. This index is also referred to as the Consumption index. Both the vacuum accumulated index and Consumption index determine the magnitude of the consumed VAE in the major pipe after a time of FCSO process.

The sucked-in liquid will travel through at least one segment leftwards along the major pipe during operation. It is clear that V_g is equal to or more than V_l, the liquid volume of a FCSO process. Liquid does not completely fill the pipe as it flows along the major pipe. This makes efficiency lower in the fluidic conveyance. The sucked-in V_g is set to vary with the sucked-in V_l and relevant conditions of the major pipeline. If a percentage is introduced for the extra sucked-in amount needed to make up the carry-efficiency drop, can be determined by the equation

$$V_g = (1+\eta)V_l \qquad (6)$$

Where η (≥0) of major pipe conditions, may vary. By means of the PVTC principle, the determination of VAE consumption in the gas phase is available to extend into a general form for associated multiple FCSO processes. Given the sucked-in gas volume of module i is V_{ig} (i=1,2,...,n), the extended operational model under the PVTC principle is as follows:

$$V_N p_- = (V_N - \sum_{i=1}^{n} V_{ig}) p_e \qquad (7a)$$

$$V_{ig} p_+ = V_{ig} p_e \qquad (7b)$$

Where i=1,2,…,n; and then it is derived as:

$$p_e = k_N p_- + \sum_{i=1}^{n} k_{ig} p_+ \qquad (8)$$

Where k_N is constant as above, while k_{ig}, the initial gaseous-cubic ratio of module i, is as follows:

$$k_{ig} = \frac{V_{ig}}{V_N} \qquad i = 1,2,...n \qquad (9)$$

So a general gaseous-cubic ratio is gained as:

$$k_G = \sum_{i=1}^{n} k_{ig} = \frac{\sum_{i=1}^{n} V_{ig}}{V_N} \qquad (10)$$

Therefore, equation (8) is modified into:

$$p_e = k_N p_- + k_G p_+ \qquad (11)$$

This equation is consistent with equation (4) of an FCSO process and shows that the consumed VAE amount of associated multiple FCSO processes are in sum of the consumed VAE amounts of the FCSO processes. The physical significance of the conclusion is rather explicit. In the case of associated or multiple FCSO processes, the sucked-in liquid of each cell is also to travel through at least one segment. If a supplement coefficient η_i, for module i, a similar equation is available to be written as:

$$V_{ig} = (1+\eta_i)V_{il}, \ i=1,2,...,n \qquad (12)$$

Where η_i may vary accordingly. Figure 3 shows the experimental results for liquid high level inside cell and pressure with time for single FCSO process. Table.1 are the VAE consumption resulting from a single FCSO process in both computation and experiment. P_{e_c} and P_{e_e} are the computation pressure and experiment pressure respectively at the fix position. These results correlate well with each other. Figure 4 shows the experimental results for liquid high level inside cell and pressure with time for FCSO processes. Table.2 are the VAE consumption resulting from the associated four FCSO processes in both computation and experiment. These results correlate well with each other.

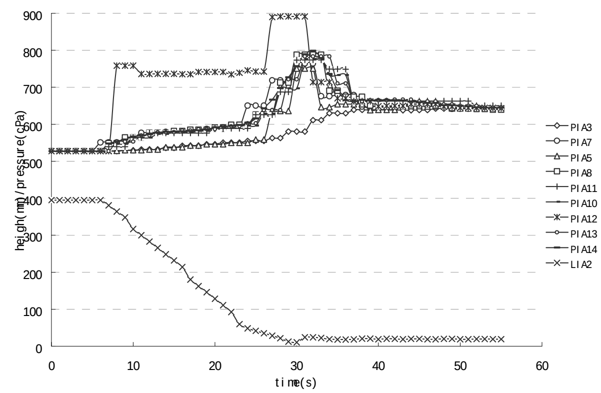

Figure.3 Gas VAE loss of single FCSO process

Tabl.1 VAE consumption result of FCSO process

	P_-(kPa)	P_+(kPa)	P_{e_c}(kPa)	P_{e_e}(kPa)
I	51.9	67.4	68.7	67.4
II	51.9	68.7	64.3	61.8

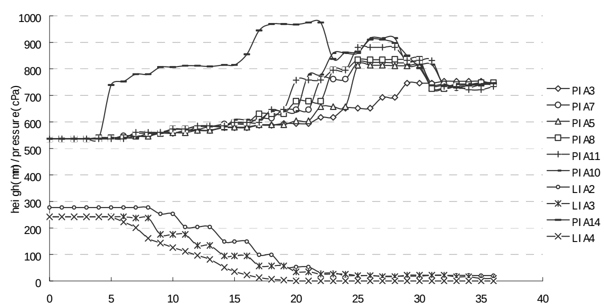

Figure.4 Gas VAE loss of joint FCSO processes

Tabl.2 VAE consumption result of FCSO processes

	P_-(kPa)	P_+(kPa)	P_{e_c}(kPa)	P_{e_e}(kPa)
I	52.1	100.9	79.9	74.4
II	53.7	100.9	79.5	74.3

If minor factors are omitted to simplify the model, the equation of actual VAE consumption becomes

$$p_e = k_N p_- + k_g p_+ + f_p(\Delta U, \psi) \quad (13)$$

Where ΔU stands for the internal energy transition; ψ for the interactive attrition, and f_p for the other additional consumption sums.

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V. VAE Loss in a Liquid Phase

In an approximately isothermal process, the interactive attrition does not take the VAE consumption of the liquid phase in an FCSO process into account. This can be analyzed in a simplified form. In the FCSO process k_V, the cubic ratio of the cell liquid to the vacuumed space in the major pipe, is designed so small as to meet $0<k_V<<1$, so the VAE consumption of the liquid phase is expressed by:

$$p_l = (1 + k_V)\, p_- \qquad (14)$$

Likely, as the individual cubic ratio k_{iv} of module i is also designed to meet $0<k_{iv}<<1$, the equations can be applied to the case for associated or multiple FCSO processes. The VAE consumption of the liquid phase is:

$$p_l = (1 + \sum_{i=1}^{n} k_{iv})\, p_- = (1 + k_V)\, p_- \qquad (15)$$

In the case of the liquid phase, the sum of cubic ratios of a number of single FCSO processes is the cubic ratio of the same associated FCSO processes in volume. This conclusion simplifies the analysis and computation of VAE consumption for the liquid phase.

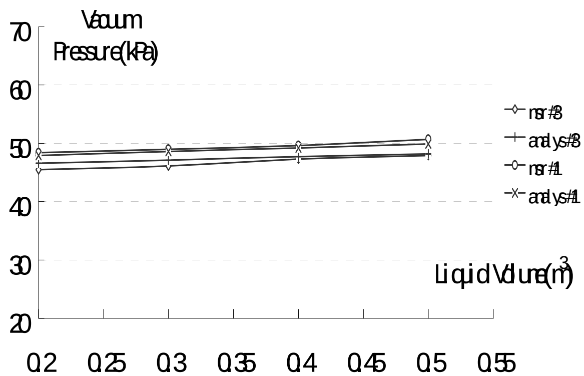

Figure.5 Liquid VAE loss of single FCSOP

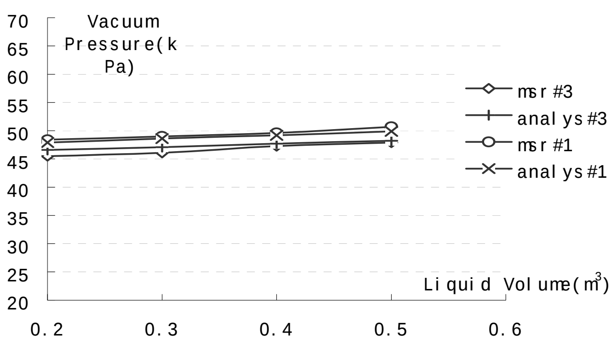

Figure.6 Liquid VAE loss of joint FCSO

For each liquid phase, model simulations of VAE consumption shown in Figures 5 and 6 of either a FCSO process or the associated FCSO processes correlate well with corresponding actual measurements. Because of the inter-phase transition loss and vapor in a FCSO process or FCSO processes, the analytical VAE consumption is slightly less than the actual. However, the VAE consumption of a liquid phase can be ignored, for in general, the total VAE consumption across a liquid phase is as small as 2-3kPa.

VI. Conclusion

T Vacuum powered fluidic conveyance is the process where vacuum energy accumulated over minutes is consumed in a matter of seconds. A measuring period of fluidic conveyance is set at the time length of a modular process. The modular process, in turn, consists of a liquid phase, a gas phase and a vacuum recovery process. A liquid phase is the one in which the accumulated liquid in a cell is sucked into the major pipe by means of vacuum power. This phase is activated only to suck in the cellular liquid, during which there is hardly variation in the density of bulky gases within the major pipe, and the corresponding VAE consumption is so minor that the amount can be ignored in engineering design. However, the subsequent gas phase is primarily responsible for the majority of VAE consumption. The state equation for a single group of gases can be developed into the state equation set for multiple groups of gases. From this, the PVTC principle is determined via simplification under the isothermal conditions. The agreement between the computational results and the experiment data shows that the PVTC principle can be applied to accurately analyze the operational model established from engineering project systems.

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