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Transient Cavitation Losses in Real-Time Multiphase Flow

Ullas Pathak¹, Daniel Theis¹, Vadim Shapiro¹

¹ Statistics & Control, Inc.

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ABSTRACT

In liquid pipelines, fluctuations in flow velocities and sudden pressure drops can allow the hydraulic pressure to drop below the vapor pressure. This leads to the formation of transient vapor cavities which negatively impact the performance of the pipeline and can damage the equipment that controls the pipeline. This article discusses the details of a method that determines the influence vaporous cavitation has on the performance of the pipeline. The method employs the use of multiphase approximations, like the Beggs-Brill method, and gas/liquid equilibrium calculations to identify regions where vapor cavities can form and to accurately determine the changes of the pressure, temperature, and mass flow rate at those regions.

INTRODUCTION AND BACKGROUND

The occurrence of transient vaporous cavitation in a liquid pipeline refers to the formation of vapor bubbles in fully filled pipes due to the evaporation of the liquid. The formation of vapor cavities can have significant impacts on the general productivity of the pipeline and on the performance of the equipment that runs the pipeline. Repeated exposure to the collapse of vapor bubbles can also create significant surface damage to the equipment that operates the pipeline.^[1]

Transient vaporous cavitation usually initiates at points along the pipeline where the pressure drops below the vapor pressure of the liquid. At the points where cavitation occurs, the flow of

the liquid/vapor mixture is usually characterized by one of the following flow regimes: A distributed flow regime where small vapor bubbles are diffused among the remaining liquid; a column separation regime where the vapor bubbles have coalesced to form large vapor pockets that are separated from the surrounding liquid.^{[1],[2]}

Traditionally the vapor pressure of the liquid has been employed to identify the regions where vapor cavities are formed. At those locations, the pressure is set equal to the vapor pressure and simple analytical formulas are used to compute the velocity of the liquid/gas mixture and the volume of the vapor cavity. Outside those regions, conventional one-dimensional simulations are performed to determine the changes that occur to the pressure and velocity of the single-phase liquid.^[3]

An alternative approach is to couple a thermodynamic treatment of liquid/vapor equilibrium with a 1-dimensional, two-phase simulation of the changes that occur to the pressure, temperature, and mass flow rate. Under this approach liquid/gas equilibrium calculations are used to identify the points/times where the single-phase liquid becomes a two-phase liquid/gas mixture.^[4] Then multiphase approximations like the Beggs-Brill method^[5] are used to compute the liquid holdup of the pipe (the fraction of the pipe's internal volume that is occupied by liquid) and perform accurate 1-dimensional simulations of both the regions that are purely liquid and the regions that are liquid/gas mixtures.^[6] The liquid holdup can also be used to determine the volume of the vapor cavity that is formed. The remainder of this paper discusses the details of this alternative method.

SCIENTIFIC APPROACH

To determine the presence, location, and size of any vapor cavity that is formed as well as the changes that occur to the liquid as it is passes through the pipeline, the pipes are separated into segments of size Δx and the change in time between each set of calculated results is equal to $\Delta t = \frac{\Delta x}{c_0}$ where c_0 is the acoustic velocity of the liquid.^[7]

At each simulation point, (x_i, t_j) , values are computed and

stored for the following properties:

- the pressure of the pipe segment, $P_{i,j}$
- the temperature of the pipe segment, $T_{i,j}$
- the exiting mass flow rate of the pipe segment, $\dot{M}_{i,j}$
- the liquid mass fraction of the exiting mass flow rate, $w_{i,j}^{L,Flow}$
- total mass of liquid and gas contained in the pipe segment, $m_{i,j}^L$ and $m_{i,j}^g$
- the mole fraction compositions of the liquid and gas phases, $y_{k,i,j}^L$ and $y_{k,i,j}^g$ (where the subscript k specifies the index of a molecular component of the two-phase mixture)

The procedure that is used to determine new values for each of the properties listed above is broken into four steps. In the first step thermodynamic liquid/vapor equilibrium calculations are performed to determine the changes that occur to the molecular compositions of the liquid and gas phases due to evaporation/condensation. The calculations also determine the changes that occur to the total mass of liquid and gas that are contained in the pipe segment.^[4]

The second step of this procedure uses the equilibrium mole fractions in cubic equations-of-state and other well-established empirical formulas to compute chemical properties (densities, heat capacities, *etc.*) for the liquid and gas phases. The equilibrium values that were determined for the total mass of liquid and gas are also used to determine average values for the chemical properties of the two-phase fluid.^[8]

The third step of this procedure uses the values that were computed for the chemical properties of the two-phase mixture in a 1-dimensional, two-phase model to compute new values for the temperature, pressure, and mass flow rate.^{[6],[7]}

The final step of this procedure uses simple mixing rules to determine the new mole fraction compositions of the liquid/gas phases of the pipe segment. The values that are computed for the new mole fractions account for the mixing that occurs between the molecular composition of the two-phase fluid that flows into the pipe segment and the molecular composition of the equilibrium liquid/gas mixture that was calculated in step 1.

Once new values have been determined for the liquid/gas mole fractions the Beggs-Brill method is used to compute a new liquid holdup for the pipe segment. The liquid holdup and mole fractions are then used to compute $m_{i,j}^L$ and $m_{i,j}^g$. If a vapor cavity is formed, the liquid holdup is also used to compute the volume of the vapor cavity. Finally, the conservation of mass is used to compute $w_{i,j}^{L,Flow}$.^[6]

Step 1. Determining the equilibrium liquid/gas compositions

Thermodynamics dictates that a layer of vapor will form above

a liquid if the fugacity of any molecular component of the liquid becomes larger than the gas phase fugacity of the component. Under those conditions, the amount of vapor will increase until the liquid and gas fugacities of each component become equal.^[9]

For a specified molecular component of the two-phase fluid, the liquid and gas fugacities can be determined using the following expressions

$$F_k^L = y_k^L \phi_k^L P \quad (1)$$

$$F_k^g = y_k^g \phi_k^g P \quad (2)$$

where the subscript k specifies the index of the selected component, F_k^L and F_k^g denote the component's liquid/gas fugacities, y_k^L and y_k^g denote the liquid/gas mole fractions of the component, ϕ_k^L and ϕ_k^g denote the liquid/gas fugacity coefficients of the component, and P denotes the pressure.^[9]

Based on equations 1 and 2 and the constraint that at equilibrium $F_k^L = F_k^g$ the following relationship can be derived for the equilibrium liquid/gas mole fractions of component k

$$y_k^g = K_k \cdot y_k^L \quad (3)$$

where $K_k = \frac{\phi_k^L}{\phi_k^g}$. Additionally, the conservation of mass requires that the equilibrium mole fractions of each component must obey the following conditions

$$y_k^{Ave} N_{Total} = y_k^g N_g + y_k^L N_L \quad (4)$$

$$N_{Total} = N_g + N_L \quad (5)$$

$$\sum_k y_k^L = 1 \quad (6)$$

$$\sum_k y_k^g = 1 \quad (7)$$

$$\sum_k y_k^{Ave} = 1 \quad (8)$$

where N_L and N_g are the total moles of liquid and gas inside the pipe segment, $N_{Total} = N_L + N_g$ is the total moles of the combined two-phase fluid inside the pipe segment, and y_k^{Ave} is the mole fraction of the combined two-phase fluid that is due to component k .^[9]

Based on the conditions listed in equations 3 – 8 the following iterative procedure can be used to determine $y_{k,i,j-1}^{L,eq}$ and $y_{k,i,j-1}^{g,eq}$, the equilibrium liquid/gas mole fractions of component k for pipe segment i at time t_{j-1} .^[4]

- The values of $y_{k,i,j-1}^L$ and $y_{k,i,j-1}^g$ are used to compute initial values for the average molecular weights of the liquid/gas phases, $MW_{L,0}$ and $MW_{g,0}$. The values of $m_{i,j-1}^L$ and $m_{i,j-1}^g$ are divided by the molecular weights to determine initial values for N_L and N_g

$$N_{L,0} = \frac{m_{i,j-1}^L}{MW_{L,0}} \quad (9)$$

$$N_{g,0} = \frac{m_{i,j-1}^g}{MW_{g,0}} \quad (10)$$

Once computed, $N_{L,0}$ and $N_{g,0}$ are used in Equations 4 and 5 to determine N_{Total} and y_k^{Ave} .

- ii. $P_{i,j-1}$, $T_{i,j-1}$, and the liquid/gas mole fractions that were determined during the previous iteration of this procedure, $y_k^{L,n-1}$ and $y_k^{g,n-1}$, are used in Peng-Robinson cubic equation of state^[10] to compute $\varphi_k^{L,n}$, $\varphi_k^{g,n}$, and $K_k^n = \frac{\varphi_k^{L,n}}{\varphi_k^{g,n}}$. (During the first iteration, $n = 0$, of this procedure $y_k^{L,0} = y_{k,i,j-1}^L$ and $y_k^{g,0} = y_{k,i,j-1}^g$)
- iii. y_k^{Ave} , $y_k^{L,0}$, and K_k^n are used in the following expression to determine the fraction of the total moles of the two-phase fluid that are part of the gas phase, $\beta_{g,n} = \frac{N_{g,n}}{N_{Total}}$.

$$\beta_{g,n} = \sum_{k \in Liq} \left\{ \frac{y_k^{Ave} - y_k^{L,n}}{\text{sign}(K_k^n - 1) \cdot \max(0.001, |K_k^n - 1|)} \right\} \quad (11)$$

where the subscript $k \in Liq$ denotes that the summation only occurs over the components of the two-phase mixture that are part of the liquid phase.

- iv. Equations 12 and 13 are used to compute new unnormalized values for the liquid/gas mole fractions of component k

$$y_k^{L,n} = \frac{y_k^{Ave}}{1 + \beta_{g,n} \cdot \{K_k^n - 1\}} \quad (12)$$

$$y_k^{g,n} = \frac{y_k^{Ave} - \{1 - \beta_{g,n}\} \cdot y_k^{L,n}}{\beta_{g,n}} \quad (13)$$

Those values are then normalized to obey equations 6 and 7.

- v. Steps ii to iv are repeated until the following condition is observed

$$\sqrt{\sum_k \{y_k^{L,n} - y_k^{L,n-1}\}^2 + \sum_k \{y_k^{g,n} - y_k^{g,n-1}\}^2} < 10^{-9} \quad (14)$$

Once the convergence criteria shown in equation 14 has been reached the final values that were computed for $y_k^{L,n}$ and $y_k^{g,n}$ are used as the equilibrium mole fractions of component k .^[4]

$$y_{k,i,j-1}^{L,eq} = y_k^{L,nLast} \quad (15)$$

$$y_{k,i,j-1}^{g,eq} = y_k^{g,nLast} \quad (16)$$

The values that were computed for $y_k^{L,nLast}$, $y_k^{g,nLast}$, and $\beta_{g,nLast}$ are also used to compute the equilibrium masses of liquid and gas in pipe segment i at time t_{j-1} .

$$m_{i,j-1}^{L,eq} = MW_{L,eq} N_{Total} \{1 - \beta_{g,nLast}\} \quad (17)$$

$$m_{i,j-1}^{g,eq} = MW_{g,eq} N_{Total} \beta_{g,nLast} \quad (18)$$

where $MW_{L,eq}$ and $MW_{g,eq}$ are the values that were computed

for the average molecular weights of the liquid/gas phases using $y_{k,i,j-1}^{L,eq}$ and $y_{k,i,j-1}^{g,eq}$.

Step 2. Calculating the chemical properties of the liquid/gas mixture

In order to solve the coupled differential equations that determine $P_{i,j}$, $T_{i,j}$, and $M_{i,j}$ reliable values must be computed for the density $\rho_{i,j-1}^{mix}$, isobaric and isochoric specific heat capacities $(C_P)_{i,j-1}^{mix}$ and $(C_V)_{i,j-1}^{mix}$, and isothermal compressibility $(\kappa_T)_{i,j-1}^{mix}$ of the two-phase mixture.^[7]

Those properties are determined by first using the Peng-Robinson cubic equation of state^[10] and other reliable empirical formulas to compute values for the chemical properties of the gas and liquid phases ($\rho_{i,j-1}^L$, $\rho_{i,j-1}^g$, etc.).^[8] Then those values are averaged using $m_{i,j-1}^{L,eq}$ and $m_{i,j-1}^{g,eq}$.

The specific formulas that are used to average the liquid/gas phase properties differ for each chemical property. For example, the average value that is required for the two-phase heat capacities is computed by using $m_{i,j-1}^{L,eq}$ and $m_{i,j-1}^{g,eq}$ to perform a mass average of the liquid and gas phase heat capacities. In contrast the two-phase density is computed by first using $m_{i,j-1}^{L,eq}$ and the internal volume of the pipe segment, V_i , to determining the liquid holdup of the pipe segment^[6]

$$\Theta_{i,j-1}^{LH} = \frac{m_{i,j-1}^{L,eq}}{\rho_{i,j-1}^L V_i} \quad (19)$$

The liquid holdup is then used to compute the volume average of the liquid and gas densities

$$\rho_{i,j-1}^{mix} = \Theta_{i,j-1}^{LH} \rho_{i,j-1}^L + \{1 - \Theta_{i,j-1}^{LH}\} \rho_{i,j-1}^g \quad (20)$$

The liquid holdup is also used in the empirical correlation function that was developed by Beggs and Brill to compute a reliable value for the friction factor of the two-phase fluid, $f_{i,j-1}^{mix}$.^{[5],[6]}

Step 3. Determining new values for the pressure, temperature, and exiting mass flow rate

The one-dimensional, two-phase model that is used to compute new values for the pressure, temperature, and mass flow rate is formed by coupling the continuity equation with the differential equations that determine the changes that occur to the momentum and internal energy of the fluid that is currently passing through the pipe segment. The mathematical expressions of those differential equations are shown in equation 21

$$\left\{ \begin{array}{l} \frac{\partial \rho_{mix}}{\partial t} + \frac{\partial(\rho_{mix} v_{mix})}{\partial x} = 0 \\ \frac{\partial(\rho_{mix} v_{mix})}{\partial t} + \frac{\partial(\rho_{mix} v_{mix}^2 + P)}{\partial x} = \Phi(x, t) \\ \rho_{mix} \left\{ \frac{\partial e_{internal}}{\partial t} + v_{mix} \frac{\partial e_{internal}}{\partial x} \right\} = S(x, t) - P \frac{\partial v_{mix}}{\partial x} \end{array} \right. \quad (21)$$

where v_{mix} denotes the velocity of the two-phase mixture, the function $\Phi(x, t)$ determines the sum of the frictional and gravitational forces that act on the fluid, and the function $S(x, t)$ determines the sum of the amount of kinetic energy that is converted into internal energy by to friction and the amount of heat that is transferred from the fluid into the surrounding environment.^[7]

At the grid point (x_i, t_j) the functions $\Phi(x, t)$ and $S(x, t)$ can be written in the following manner

$$\begin{aligned} \Phi_{i,j} &\equiv \Phi(x_i, t_j) \\ &= - \frac{f_{i,j}^{mix} \rho_{i,j}^{mix} v_{i,j}^{mix} |v_{i,j}^{mix}|}{2D_i} - g \rho_{i,j}^{mix} \sin(\theta_i) \end{aligned} \quad (22)$$

and

$$\begin{aligned} S_{i,j-1} &\equiv S(x_i, t_j) \\ &= \frac{f_{i,j-1}^{mix} \rho_{i,j-1}^{mix} \{v_{i,j-1}^{mix}\}^3}{2D_i} - \frac{4h_i \{T_{i,j-1} - T_{amb}\}}{D_i} \end{aligned} \quad (23)$$

where

- $v_{i,j}^{mix}$ denotes the velocity of the two-phase mixture that passes through segment i at time t_j
- D_i denotes the internal diameter of the pipe
- θ_i denotes the angle that the pipe makes with the horizontal
- g denotes the acceleration due to gravity
- h_i denotes the overall heat transfer coefficient of the fluid at the specified time and location
- T_{amb} denotes the ambient temperature of the environment that surrounds the pipe.

In chapter 5 of *Modeling of Oil Product and Gas Pipeline Transportation*, M. V. Lurie discusses how the method of characteristics can be used to solve equation 21.^[7] From that discussion the following equations are derived for $P_{i,j}$, $T_{i,j}$, and $\dot{M}_{i,j}$

$$v_{i,j}^{mix} = \frac{1}{c_0} \cdot \frac{B_{i,j}^{(+)} - B_{i,j}^{(-)}}{\rho_{i-\frac{1}{2},j-1}^{mix} + \rho_{i+\frac{1}{2},j-1}^{mix}} \quad (24)$$

$$P_{i,j} = B_{i,j}^{(+)} - c_0 \rho_{i-\frac{1}{2},j-1}^{mix} v_{i,j}^{mix} \quad (25)$$

$$\dot{M}_{i,j} \approx A_i \rho_{i,j-1}^{mix} v_{i,j}^{mix} \quad (26)$$

$$\begin{aligned} T_{i,j}^{2p} &= T_{i-\frac{1}{2},j-1}^{2p} + \frac{\Delta t}{c_p} \cdot \left(\frac{S}{\rho_{mix}} \right)_{i-\frac{1}{2},j-1} \\ &+ \frac{1}{(C_p)_{i-\frac{1}{2},j-1}} \cdot \left(\frac{P}{\rho_{2p}^2} \right)_{i+\frac{1}{2},j-1} \cdot \left\{ P_{i,j}^{2p} - P_{i-\frac{1}{2},j-1}^{2p} \right\} \end{aligned} \quad (27)$$

where

$$v_{i,j-1}^{mix} = \frac{M_{i,j-1}}{\rho_{i,j-1}^{mix} A_i} \quad (28)$$

$$B_{i,j}^{(\pm)} = P_{i\mp\frac{1}{2},j-1} \pm c_0 \rho_{i\mp\frac{1}{2},j-1}^{mix} v_{i\mp\frac{1}{2},j-1}^{mix} + \Delta t \cdot I_{i\mp\frac{1}{2},j-1}^{(\pm)} \quad (29)$$

$$R_{i,j-1} = \frac{1}{P_{i,j-1} \cdot (\kappa\tau)_{i,j-1}} \cdot \left\{ \frac{(C_p)_{i,j-1}^{mix}}{(C_v)_{i,j-1}^{mix}} - 1 \right\} \quad (30)$$

$$I_{i,j-1}^{(\pm)} = R_{i,j-1} S_{i,j-1} \pm c_0 \Phi_{i,j-1} \quad (31)$$

In equations 24–31, the values that are needed for each of the properties (P , T , v , B , ...) at the points $x_{i+\frac{1}{2}}$ and $x_{i-\frac{1}{2}}$ are computed using the following formula

$$\mathcal{O}_{i\pm\frac{1}{2},j-1} = \frac{1}{2} \cdot \{ \mathcal{O}_{i\pm 1,j-1} + \mathcal{O}_{i,j-1} \} \quad (32)$$

where \mathcal{O} specifies the property of interest (*i.e.* $\mathcal{O} = P, T, \dots$).

Step 4. Determine new values for the mass of liquid and gas in each pipe segment

The final step in this procedure is to determine new values for $y_{k,i,j}^L$, $y_{k,i,j}^G$, $m_{i,j}^L$, $m_{i,j}^G$, and $w_{i,j}^{L,Flow}$. Using the liquid and gas mole fraction compositions of pipe segment $i-1$ the total moles of liquid and gas that flow into pipe segment i can be computed

$$N_{i-1,j}^{L,Flow} = \left\{ \frac{w_{i-1,j}^{L,Flow} \dot{M}_{i-1,j}}{MW_{L,Flow}} \right\} \cdot \Delta t \quad (33)$$

$$N_{i-1,j}^{G,Flow} = \left\{ \frac{(1 - w_{i-1,j}^{L,Flow}) \dot{M}_{i-1,j}}{MW_{G,Flow}} \right\} \cdot \Delta t \quad (34)$$

where $MW_{L,Flow}$ and $MW_{G,Flow}$ denote the average molecular weights of the liquid and gas phases in pipe segment $i-1$. The values that were determined for $N_{i-1,j}^{L,Flow}$ and $N_{i-1,j}^{G,Flow}$ are then used to compute the values of the liquid/gas mole fraction compositions of pipe i for time t_j

$$y_{k,i,j}^L = \frac{N_{i,j-1}^{L,eq} \cdot y_{k,i,j-1}^L + N_{i-1,j}^{L,Flow} \cdot y_{k,i-1,j}^L}{N_{i,j-1}^{L,eq} + N_{i-1,j}^{L,Flow}} \quad (35)$$

$$y_{k,i,j}^G = \frac{N_{i,j-1}^{G,eq} \cdot y_{k,i,j-1}^G + N_{i-1,j}^{G,Flow} \cdot y_{k,i-1,j}^G}{N_{i,j-1}^{G,eq} + N_{i-1,j}^{G,Flow}} \quad (36)$$

where $N_{i,j-1}^{L,eq}$ and $N_{i,j-1}^{G,eq}$ are the moles of liquid and gas in pipe segment i at time t_{j-1} after liquid/vapor equilibrium is reached.

The new molecular compositions and new values that were determined for $P_{i,j}$, $T_{i,j}$, and $\dot{M}_{i,j}$ are then used in the Beggs-Brill approximation to determine a new value for the liquid

holdup of the pipe segment, $\Theta_{i,j}^{LH}$.^{[5],[6]} A new value is also computed for the liquid density, $\rho_{i,j}^L$.

The values that were determined for the liquid holdup and liquid density are used in the following formula to compute a new value for the total mass of liquid in pipe segment i at time t_j

$$m_{i,j}^L = \rho_{i,j}^L \Theta_{i,j}^{LH} V_i \quad (37)$$

where V_i is the internal volume of pipe segment i .

The entering and exiting flow rates can also be used to compute the value of the combined mass of liquid and gas in pipe segment i at time t_j

$$m_{i,j}^{Total} = m_{i,j-1}^{Total} + \{\dot{M}_{i-1,j} - \dot{M}_{i,j}\} \cdot \Delta t \quad (38)$$

where $m_{i,j}^{Total} = m_{i,j}^L + m_{i,j}^g$. Subtracting the value that was determined for $m_{i,j}^L$ from the value that was determined for $m_{i,j}^{Total}$ gives the total mass of gas in pipe segment i at time t_j , $m_{i,j}^g = m_{i,j}^{Total} - m_{i,j}^L$.

The liquid holdup and the internal volume of the pipe segment can also be used to determine the total volume of vapor in the pipe segment

$$V_{i,j}^g = \{1 - \Theta_{i,j}^{LH}\} V_i \quad (39)$$

That volume is the volume of the vapor cavity that forms in the pipe segment.

Finally, the following formula is used to compute a new value for the liquid mass fraction of the total exiting mass flow rate

$$w_{i,j}^{L,Flow} = \frac{1}{\dot{M}_{i,j}} \cdot \left\{ w_{i-1,j}^{L,Flow} \dot{M}_{i-1,j} - \left(\frac{m_{i,j}^L - m_{i,j-1}^L}{\Delta t} \right) \right\} \quad (40)$$

CONCLUSIONS

A model was proposed for the accurate simulation of transient cavitation. An implementation of the model is being developed using existing modules that were created to predict the condensation of liquid in gas pipelines. Once the method is fully implemented, benchmark calculations will be performed and the results of those calculations will be published in a future journal article.

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AUTHOR BIOGRAPHY

Ullas Pathak is a Technology Manager working at Statistics & Control, Inc. He currently works on developing automation architecture, quantitative modeling, optimization strategies for unit control systems, and process dynamics. Ullas has a Bachelor of Technology in Chemical Engineering from the National Institute of Technology Tiruchchirappali (NIT Trichy), a Master of Science in Chemical Analytics from Arizona State University, and a Master of Engineering in Biorenewable Technologies from Iowa State University. Ullas has led many global-energy projects, focusing on optimizing operations, process enhancement and product engineering.

Daniel Theis is a software engineer working at Statistics & Control, Inc. He has a Bachelor of Science in Chemistry from Bethel College, a Master of Science in Physical Chemistry from the University of Minnesota, and a Doctorate in Computational Chemistry from the University of North Dakota. Daniel has over 10 years of experience in the development and use of computer software designed to predict the properties and behavior of complex chemical systems.

Vadim Shapiro is co-founder and President of *Statistics & Control, Inc.* He manages all aspects of engineering, including development of the company's *OptiRamp*® Advanced Process Control software. Vadim Shapiro has over 20 years' leadership

experience in systems and software engineering, project management, and product development in the field of turbo machinery control, advanced process control, and power management systems. Vadim Shapiro holds six patents in the area of turbomachinery control and advanced process control,

with several applications pending.