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Novel Control System for Multi-Effect Evaporator Incorporating Cascade and Feed-Forward Controls

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Abstract: Chemical recovery is one of the most important processes in kraft pulping. In this process, the used chemicals that are left behind during cooking are recovered. After the cooking process is over, these chemicals have a very low concentration in the liquor, usually 13% to 18%. Before they can be recovered, their concentration needs to be raised to at least 60%. This is achieved via evaporation process using superheated steam in either a single evaporator or, more commonly, in multiple evaporators working in cascade, called as multi-effect evaporator. In this paper, the development of a control system for a 3-effect evaporator is presented. It incorporates three novel features: (a) The problem of an inherent interaction between successive evaporators is effectively taken care by using cascade control. There is a primary PID controller that gets the actual value of solid concentration in the liquor as the feedback and to which the required (target) value of concentration is given as the set-point. Its output is the required value of steam flow rate, which is applied to a secondary PID controller as the latter's set-point. The secondary controller controls the flow rate of superheated steam, which is the manipulated variable of the evaporation process. (b) Another major problem in the control of the multi-effect evaporation process is long propagation time of a load disturbance through a series of evaporators. This is overcome here by incorporating a feed-forward control. The disturbance is sensed right at the input and a correction is added in the forward path immediately. (c) The third novel feature of the control system is the use of boiling point rise (BPR) technique of indirect measurement of solid concentration (which is the controlled variable). The technique is based on the measurement of two temperatures and a pressure and needs only standard sensors and data acquisition. It permits a fast and online measurement of concentration. The three features result in an accurate and fast control in-spite of the complexities of the multi-effect evaporation process.
Keywords: Boiling point rise, cascade control, chemical recovery, concentration, evaporators, feed-forward control, multi-effect, Kraft pulping, PID controller.

I. INTRODUCTION

Chemical recovery process is one of the most important processes that constitute *Kraft pulping*. Here the used chemicals left behind in the *cooking process* are recovered [1]. The waste product from the *digester*, called as *black liquor*, has only 13 to 18% of solid content in it. The black liquor enters into the *recovery cycle* at the evaporation phase. Here, the solid concentration in the weak liquor is increased by *evaporation process* carried out in vessels, called as evaporators, using superheated steam for heating. Generally, multiple evaporators connected in cascade, called as multi-effect evaporators, are used for increasing efficiency of heat utilization. Superheated steam is fed to the first evaporator and after it has given away some of its heat is fed to the next evaporator, and so on. The weak liquor enters the last evaporator and after partial evaporation goes to the next evaporator. On completion the evaporation process, thick liquor with desired concentration value comes out of the first evaporator, subject to a proper closed loop control of the process. Schematic of a 6-effect evaporator is shown in Figure 1.

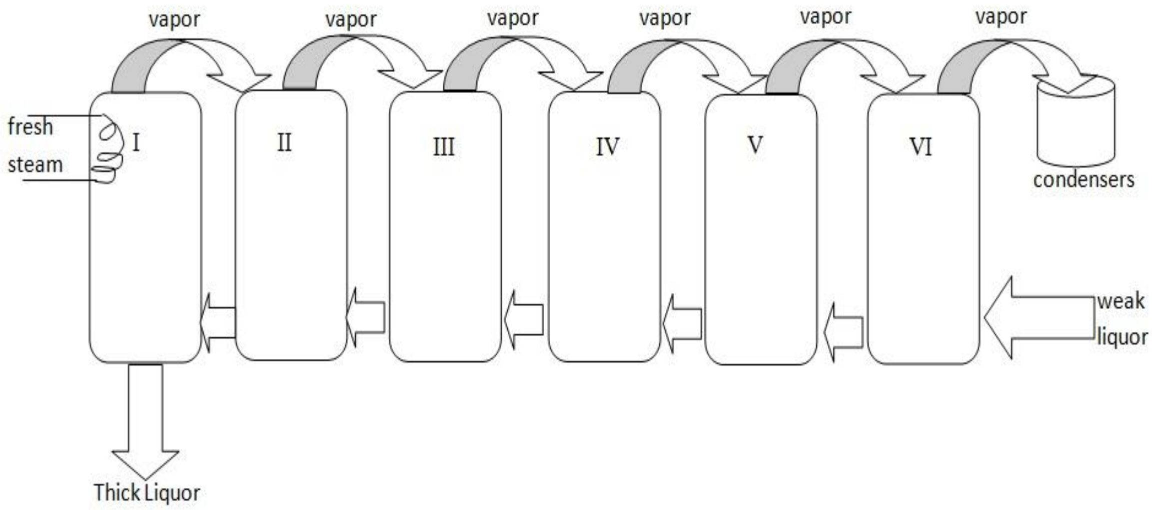

Fig.1. Schematic of a 6-effect evaporator

The thick liquor is then fed to a chemical *recovery boiler*. The recovery boiler is a *chemical reactor* that is used for the recovery of the used chemicals [1]. The heat generated during the combustion of the dissolved organic and inorganic materials is used for the generation of electricity. The burned liquor is converted to a substance called *smelt*. This smelt is dissolved in water or a weak *white liquor*, which forms an aqueous solution, called *green liquor*. The green liquor undergoes *causticization*, in which lime mud is separated from the white liquor. The lime mud is burned with a fuel to release carbon dioxide and leave behind lime, which can be reused in causticization, while the separated white liquor is sent to the digester for use again in cooking.

The thick liquor leaving the evaporation process is expected to have a concentration ranging from 60 to 70% [2]. A proper control system is essential to ensure (a) high accuracy of this concentration with respect to the set-point, and (b) fast action. Frank Joachim and Mayer Z. Heringdort reported the development of a flexible microprocessor-based evaporation controller in 2012 [3]. In 2016, Aminu Tijjani, H.K. Verma and Chhaya Sharma reported the development of a PID controller for single-effect evaporator [4]. The multi-effect evaporation process is far more complex than the single-effect evaporation process, as the output of one evaporator goes to next evaporator in the series as latter's input. This gives rise to two problems: one, of an interaction between successive evaporators and two, of a long propagation time of disturbances from the first to the last evaporator. This paper presents a control system for multi-effect evaporator, which is aimed at: (a) ensuring high accuracy of solid concentration in the outgoing liquor vis-à-vis the set-point, and (b) a fast response to any disturbance in the input liquor.

II. CASCADE CONTROL FOR MULTI-EFFECT EVAPORATOR

Control of multi-effect evaporators is different from that of a single evaporator. This is because in multi-effect evaporators, the output of one evaporator is used as the input to the next one. As such, the behavior of every evaporator is influenced by what it receives from the preceding one. Cascade control can provide an effective overall control of multi-effect evaporators, as it takes care of the interaction between the successive evaporators. Figure 2 illustrates the concept of cascade control, which involves two control loops, each loop being controlled by a separate PID controller. One controller is called the primary controller, while the other one is called the secondary controller. The former controls the controlled variable while the latter controls the manipulated variable [5]. The primary controller is given a set-point based on the desired output of the controlled variable, while the output of the primary controller is used as the set-point of the secondary controller.

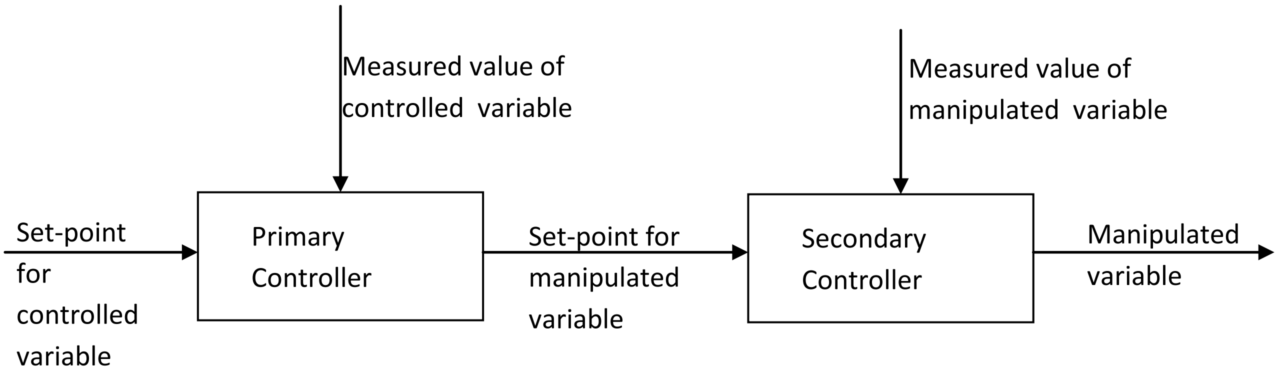

Fig. 2. Block schematic of a simple cascade control

Figure 3 shows the cascade control of a 3-effect evaporator. Here, solid concentration of the liquor (C) is the controlled variable while the flow rate of the steam used for evaporation is the manipulated variable. C_{sp} is the concentration set-point of the primary PID controller (that is, the desired value of solid concentration), while C_a is the actual solid concentration in the thick (output) liquor and applied as feedback. Output of the primary controller is the desired steam flow-rate, which acts as the set-point of the secondary PID controller. The actual value of the flow rate of steam input to evaporator-1 is used as the feedback to the secondary controller, as shown in the figure.

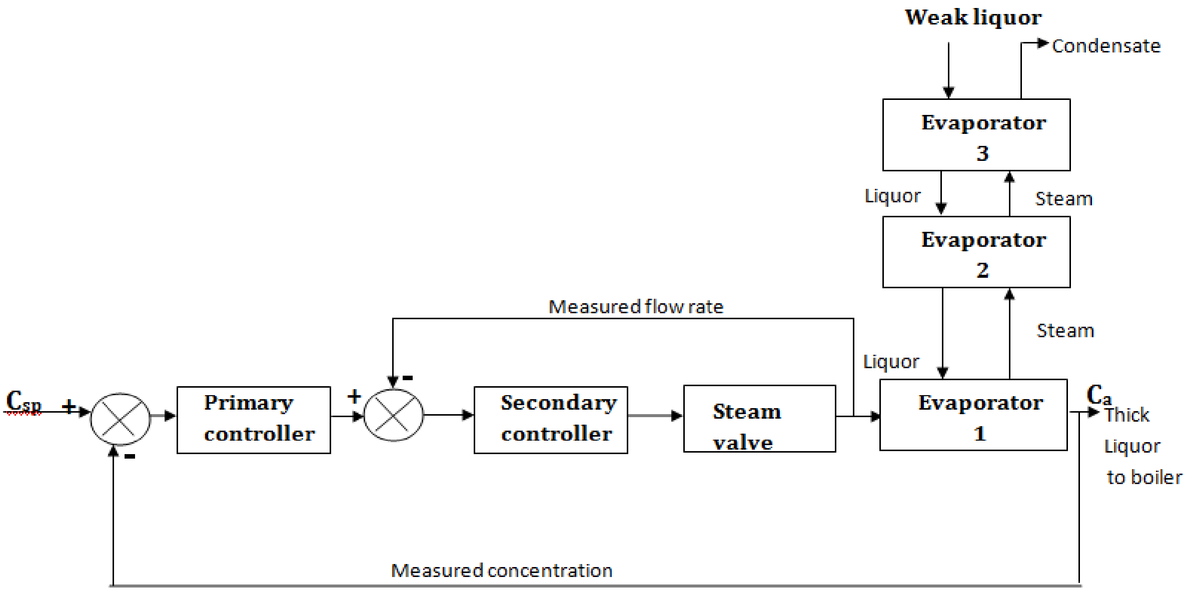

Fig. 3. Block schematic of the cascade control of 3-effect evaporator
(C_{sp} = Concentration set-point, C_a = Actual concentration)

III. BOILING POINT RISE (BPR) AS A MEASURE OF CONCENTRATION

The primary PID controller, as explained earlier, uses the actual concentration of the output liquor as the feedback. This requires a continuous measurement, preferably an online measurement, of the concentration. No easy technique of online direct measurement of solid concentration in liquors is available. Hence, an indirect measurement technique based on boiling point rise (BPR) has been opted for in the present research work.

BPR is defined as the difference between the boiling temperatures of a given solution and its pure solvent at the same pressure [6]. If one can measure the two temperatures as well as the pressure at which the liquor and pure water boil, then the solid concentration (x) in the boiling liquor can be calculated from the statistical equations (1) and (2) given below, which are based on the investigations by Zaman and Fricke on slash pine black liquor [7].

$$BPR = (a_1 + b_1 p_r)[(x/_{1-x})] \quad for\ x < 0.65 \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$BPR = [(a_2 + b_2 p_r) + (a_3 + b_3 p_r)][(x/_{1-x})] \quad for\ x \geq 0.65 \quad \ldots\ldots\ldots \quad (2)$$

where a1, a2, a3, b1, b2 and b3 are the constants to be determined experimentally in advance for the given type of liquor and p_r is the evaporator pressure.

BPR is calculated from the two measured temperatures. From this value of BPR and the measured value of pressure p_r, the concentration is evaluated from equation (1) assuming that it is less than 65%, that is, $x < 0.65$. If this value x turns out to be greater than or equal to 0.65, then equation (2) is used for calculating a more correct value of x.

IV. CONTROL SYSTEM INCORPORATING CASCADE CONTROL AND BPR TECHNIQUE FOR CONCENTRATION MEASUREMENT

Figure 4 shows block schematic of the cascade control system for 3-effect evaporation process, wherein the actual concentration of the output liquor is measured online using the BPR technique and fed to the primary PID controller. The desired concentration is written into the primary controller, which acts as its set-point. This set-point is normally chosen in the range of 60% to 70%. Three sensors are used for the purpose of indirect measurement of the concentration. A temperature sensor is placed at the steam inlet to measure the temperature of the steam, T_1. Another temperature sensor is placed inside the liquor just below the surface to measure its boiling temperature, T_2. At the same time, a pressure sensor connected to the head of evaporator-1 measures the pressure inside the evaporator, p_r. The analog outputs of the three sensors are sent to an ADC through a multiplexer. Their digital values are subsequently used for computing the value of actual solid concentration in the liquor, which is then used by the primary PID controller as the feedback. The actual flow rate of the steam is measured by placing a flow sensor, (with digital output), F, in the inlet to evaporator-1 and applied to the secondary PID controller as the feedback, as shown in the figure.

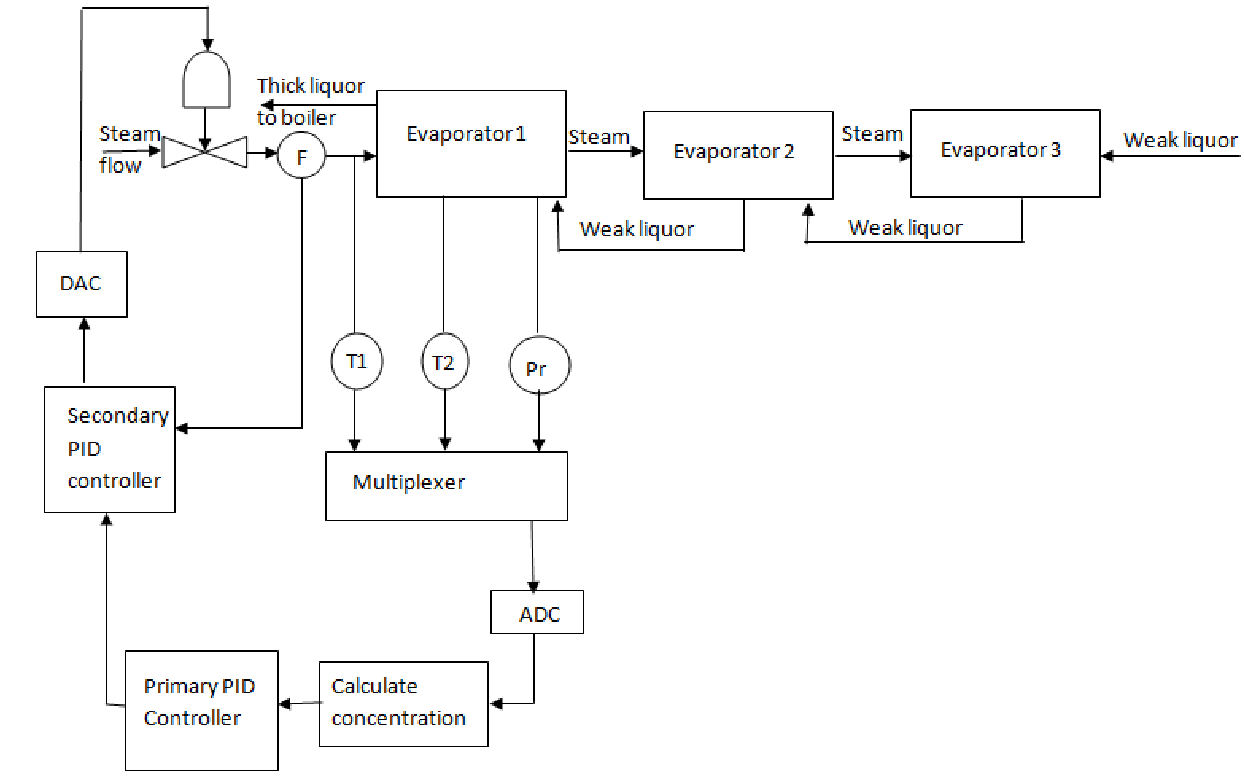

Fig. 4. Block schematic of proposed cascade control of 3-effect evaporator using BPR technique for concentration measurement

(T = temperature sensor, P_r = pressure sensor, f = flow rate sensor).

V. ADDITION OF FEED-FORWARD CONTROL

The multi-effect evaporator receives its input, that is, the week liquor, from the preceding cooking process. Any changes occurring in the cooking process or even in an earlier process, can change either the flow rate of the week liquor, or the solid concentration in it, or both. This becomes a disturbance in the input (load) of the evaporation process. Left to itself, this disturbance must propagate through various evaporators before the primary and secondary PID controllers of evaporator-1 can take a corrective action, see figure 3. This delay in action due to the propagation time can cause a *considerable deviation* in the concentration of the thick output liquor from the set-point for a *considerably long time.* As the number of evaporators in a multi-effect evaporation process increases (typically, 6 or 7 evaporators are used), the delay in the correction would become longer and longer, and the problem would become more serious in magnitude.

The problem can be overcome by incorporating feed-forward control in the control system [8]. Figure 5 shows the control system for the 3-effect evaporator incorporating feed-forward control as well as cascade control. For the feed-forward control, shown by dotted lines, the concentration and flow rate of the weak input liquor are measured and their values are used for calculating the necessary correction in the opening of the steam valve of evaporator-1. Thus, a correction is initiated as soon as the disturbance occurs.

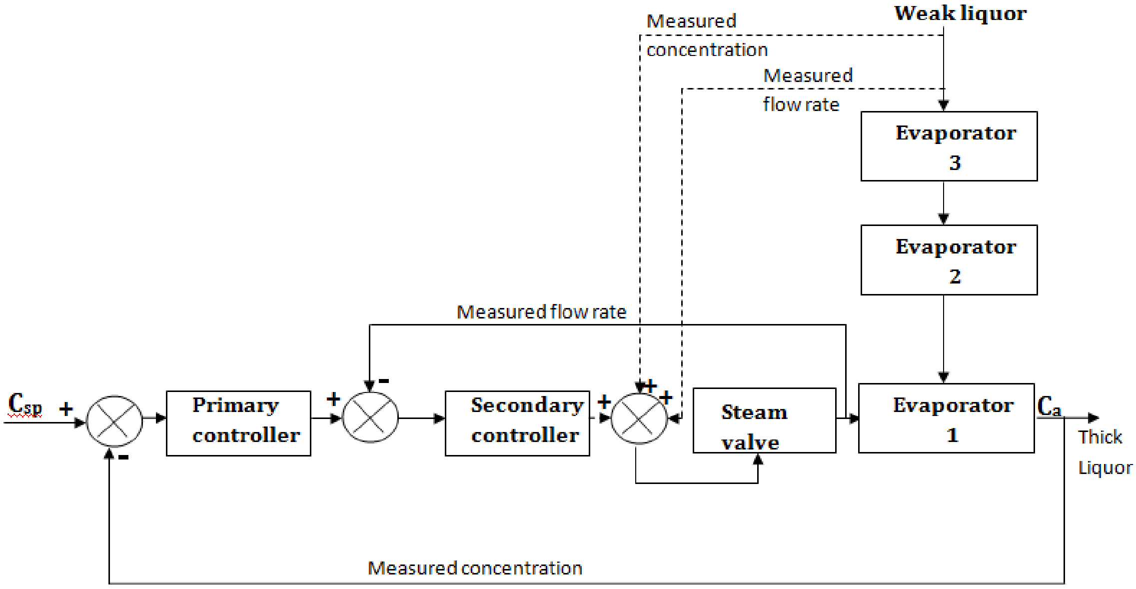

Fig.5 Block schematic of the control system incorporating both cascade and feed-forward controls.

VI. CONTROL SYSTEM INCORPORATING CASCADE AND FEED-FORWARD CONTROLS AND BPR TECHNIQUE

A block schematic of the control system, incorporating both cascade and feed-forward controls and online (indirect) measurement of the actual solid concentration in thick output liquor leaving evaporator-1, is shown in figure 6. This is the final control system for the 3-effect evaporator, which combines the advantages of cascade control, feed-forward control and the BPR technique. The control system takes care of the interaction between successive evaporators through the cascade control and provides immediate (forward) correction in the steam flow rate in response to any disturbance in the input to the process (weak liquor). The BPR technique allows a fast measurement of solid concentration in the thick output liquor through simple online measurements of two temperatures and one pressure using standard sensors and data acquisition followed by some calculations. For the feed-forward control, accurate measurements of concentration and flow rate (‘C’ and ‘F’ in the figure) of the weak liquor are not necessary. Some inexpensive, even offline, technique of concentration measurement will serve the purpose. Similarly, a low-cost low-precision flow-meter would be good enough.

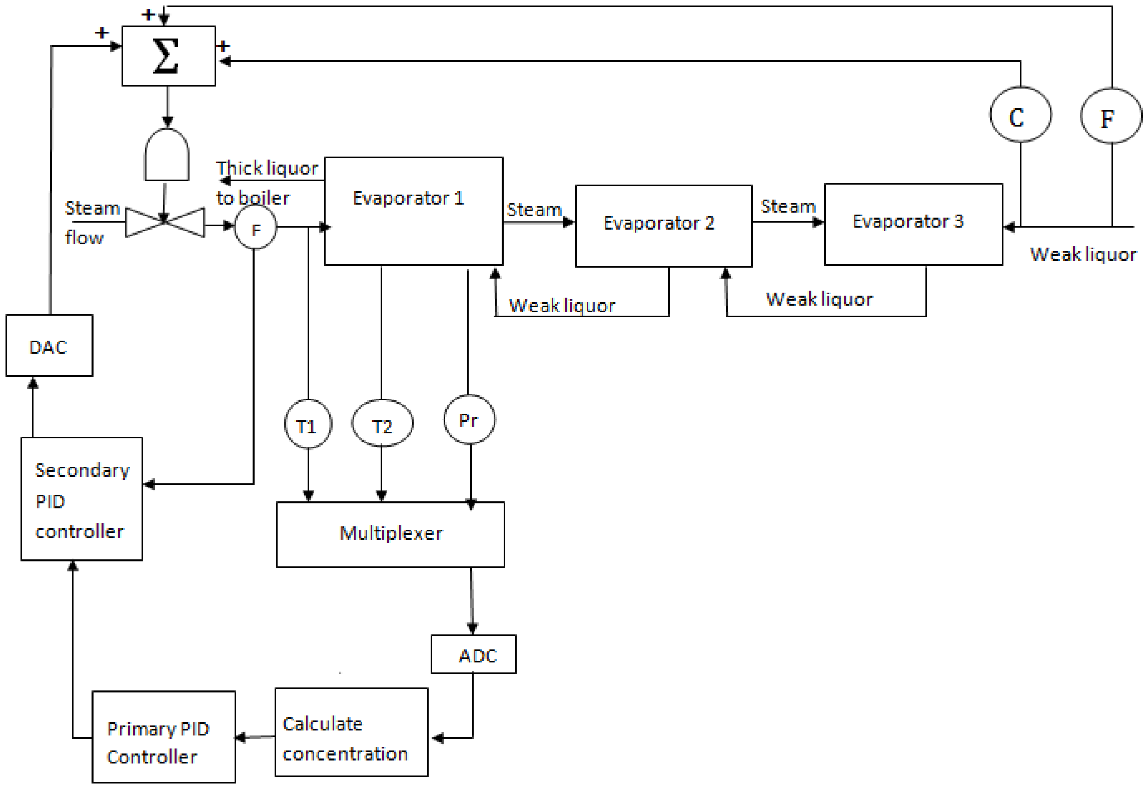

Fig. 6 Block schematic of the control system incorporating cascade and feed-forward controls and concentration measurement by BPR technique
(C = Concentration measurement, F = Flow measurement)

VII. CONCLUSION

The multi-effect evaporation process is far more complex than the single-effect evaporation process, as the output of one evaporator serves as the input to the evaporator it precedes. This problem of an interaction between successive evaporators has been effectively taken care here by using cascade control instead of the conventional/simple feedback control. There is a primary PID controller that gets the actual value of concentration as the feedback and to which the required (target) value of concentration is given as the set-point. Its output is the required value of the steam flow rate, which is applied to a secondary PID controller as the latter's set-point. The secondary controller controls the steam flow rate, which is the manipulated variable of the evaporation process.

Another major problem in the control of the multi-effect evaporation process is the long propagation time of a load disturbance through a series of evaporators. This has been overcome here by incorporating a feed-forward control. The disturbance is sensed right at the input and a correction is added in the forward path immediately.

The third novel feature of the control system is the use of boiling point rise (BPR) technique of indirect measurement of solid concentration in the thick output liquor (which is the controlled variable). As the technique is based on the measurement of two temperatures and a pressure, commonly used sensors and data acquisition circuit can serve the purpose very well. This approach permits a fast and online measurement of concentration, thus making the control loop act fast and the control system inexpensive.

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