

Dec. 5, 1967

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3,356,590

CONTROLLING A DISTILLATION OPERATION TO MAINTAIN SPECIFIED
PRODUCT PURITIES WITH OPTIMUM FEED ENTHALPY

Original Filed Dec. 26, 1962

2 Sheets-Sheet 1

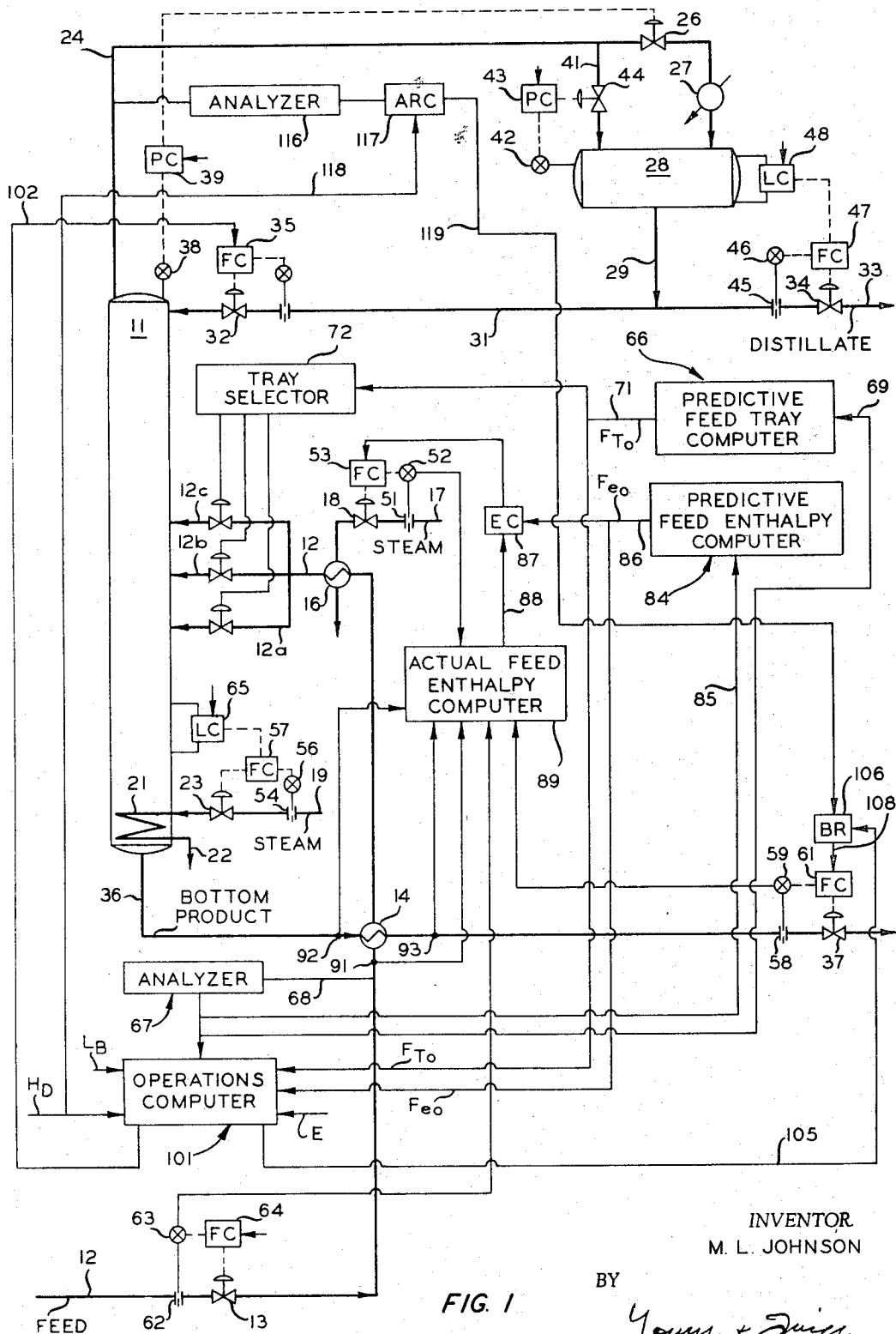


FIG. 1

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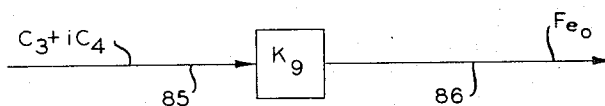


FIG. 4

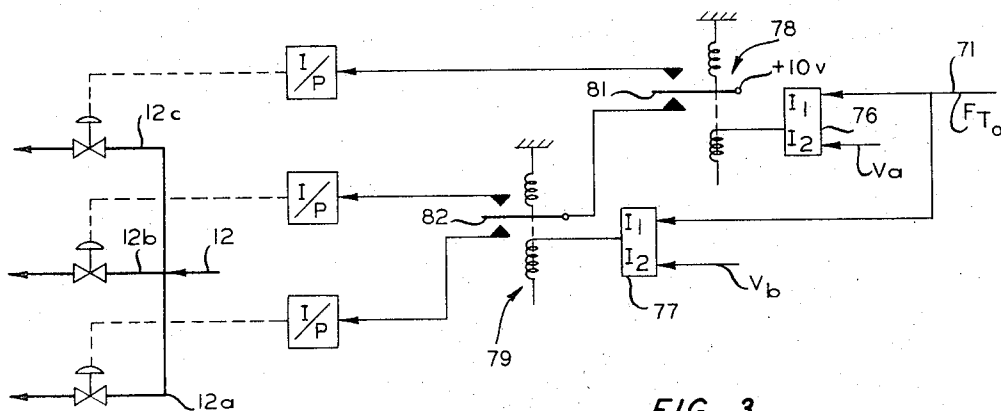


FIG. 3

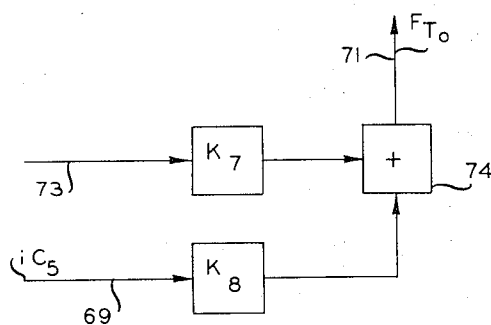


FIG. 2

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CONTROLLING A DISTILLATION OPERATION TO MAINTAIN SPECIFIED PRODUCT PURITIES WITH OPTIMUM FEED ENTHALPY
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Continuation of application Ser. No. 246,987, Dec. 26, 1962. This application Jan. 13, 1967, Ser. No. 609,259
4 Claims. (Cl. 203—1)

This is a continuation of application Ser. No. 246,987, filed Dec. 26, 1962.

This invention relates to controlling the operation of a distillation column. In another aspect, it relates to a method and apparatus for determining which of several trays in a distillation column is the optimum feed tray necessary to produce products of predetermined specifications from a particular feedstock with a minimum column heat input. In another aspect, it relates to a method and apparatus for automatically introducing the feedstock onto the so-determined optimum feed tray. In another aspect, it relates to a method and apparatus for determining what is the optimum enthalpy of a feedstock to a distillation column necessary to produce products of predetermined specifications for such feedstock with minimum column heat input. In a further aspect, it relates to a method and apparatus for controlling the heating of the feedstock in accordance with the so-determined optimum feed enthalpy.

There is ever-increasing activity in the art of fractional distillation to optimize the operation of a distillation column so that fractions or products (usually distillate and bottom products) with desired specifications can be produced at minimum operating levels. Optimizing the operation of a distillation column is complicated, difficult and tricky because of the column's numerous degrees of freedom, which are characterized as independent variables, some of which are controllable, e.g., feed temperature and reboiler heat, and others which are uncontrollable, e.g., feed flow rate and feed composition. Two important input variables, and of primary concern in this invention, are those of feed tray location and feed enthalpy.

For optimum operation of the column, the feed tray location should be manipulated when significant changes in feed composition and/or product specifications occur. However, in practice feed tray location is often treated for long periods of operation (e.g., a year or longer) as a constant, because of the complexity of the operation and a lack in sufficient and continuous operation data, notwithstanding changes in feed composition and/or product specifications. The operator in practice will usually estimate the "best" feed tray location for one feed composition, or a limited range of feed compositions, or for one set of conditions, and then not alter the location of the feed tray or only alter it infrequently. This mode of operation is usually far from optimum and often results in excess utility load and costs, lower process capacity, higher initial investment, and the products produced may be off-specification and necessitate further fractionation in yet another column in order to produce products which do meet specifications.

In many distillation columns the feed introduced into the column is heated, usually by first indirectly heat exchanging it with the bottom product and then with steam. It becomes necessary, for efficient and economical operation, to maintain the enthalpy or heat content of the thus-heated feed at a constant value for a given operation, notwithstanding changes in feed flow rate and/or feed composition. Here, again, it has been the practice for the operator to determine what the feed enthalpy should be for a particular feed composition, or range of compositions, or for a particular flow rate, and then not alter the heating of the feed or only alter it infrequently. Such mode of

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operation also is far from optimum and often results in excess utility load and costs, etc.

Accordingly, an object of this invention is to improve the operation of a distillation column. Another object is to provide an improved method and apparatus for determining which of several trays in a distillation column is the optimum feed tray necessary to produce products of desired specifications from a particular feed stock at minimum column heat input. Another object is to provide an improved method and apparatus for automatically introducing the feedstock onto the so-determined feed tray. Another object is to provide an improved method and apparatus for determining what is the optimum enthalpy of a distillation column feed stream necessary to produce products of desired specifications from such feedstock at minimum column heat input. Another object is to control the heating of the feedstock in such a manner as to control the feed enthalpy thereof and perform this operation at minimum column heat input. Another object is to treat feed tray location and feed enthalpy as independent controllable variables and manipulate them, thereby minimizing utility load and costs, increase process capacity, and make it unnecessary to over-design the column for want of control over these variables. Further objects and advantages of this invention will become apparent to those skilled in the art from the following discussion, appended claims, and accompanying drawing in which:

FIGURE 1 is a schematic diagram of a distillation column provided with certain features of this invention;

FIGURE 2 is a schematic diagram of certain mathematical analog instrumentation which can be used to determine feed tray location for the column illustrated in FIGURE 1;

FIGURE 3 is a schematic diagram of certain instrumentation which can be used to introduce feedstock onto one of several trays of the column of FIGURE 1 in accordance with a determination of the optimum feed tray; and

FIGURE 4 is a schematic diagram of certain mathematical analog instrumentation which can be used to determine the optimum feed enthalpy of a feedstock.

To provide a setting or background for the subject invention, there will be described in brief fashion a conventional distillation column, illustrated in FIGURE 1.

In FIGURE 1, there is shown a conventional fractional distillation column 11, which can be provided with a plurality of vertically spaced liquid-vapor contact trays (not shown). Feed comprising a multi-component mixture to be separated is supplied via line 12 and introduced, via one of feed tray supply lines 12a, 12b, 12c, onto a feed tray in column 11 located at an intermediate level therein, the flow rate of the feed being controlled by valve 13. Feed line 12 is associated with an indirect heat exchanger or economizer 14 and an indirect heat exchanger or preheater 16. An indirect heat exchange medium such as steam is supplied via line 17 to preheater 16, the flow rate of the heat exchange medium being controlled by valve 18. Heat is supplied to the kettle of column 11 by circulation of steam or other heat exchange medium from supply line 19 through reboiler coil 21, the heat exchange medium being withdrawn from the kettle via line 22. The flow rate of the heat exchange medium in line 19 is controlled by valve 23. Vapors are removed from the top of column 11 through overhead line 24, the flow rate being controlled by valve 26, and passed through a cooler 27 such as an air-cooled condenser, the resulting liquid being passed to an accumulator 28. Liquid distillate in accumulator 28 is withdrawn via line 29, and a portion of this withdrawn liquid is recycled via line 31 as external reflux to the top of column 11, the flow rate of the external reflux being controlled by valve 32. The balance of the liquid distillate withdrawn from accumulator 29 is removed from

the system through line 33 and yielded as distillate product, the flow rate being controlled by valve 34. Bottom product is withdrawn from the kettle of column 11 via line 36 and it is passed in indirect heat exchange relationship through economizer 14 with the feed in line 12, the flow rate of the bottom product being controlled by valve 37.

Thus far, there has been described a conventional distillation column, which by itself does not constitute the subject invention. The object of the distillation column, of course, is to separate the multi-component feed into at least two fractions, an overhead and a bottom product. The light components of the feed will appear mainly in the overhead and the heavy components of the feed will appear mainly in the bottom product. The light components will comprise a light component and components lighter than the light component, while the heavy components will comprise a heavy component and components heavier than the heavy component. Since perfect separation between the light component and the heavy component is impossible, some of the heavy component will appear as an impurity in the overhead (and thus in the distillate product) and some of the light component will appear as an impurity in the bottom product. However, the amounts of these impurities can be kept down to desired levels by proper operation of the column. The operation of a distillation column can be specified by specifying the fraction (H_D) of the heavy key component desired in the overhead (or distillate product) and the fraction (L_B) of the light key component desired in the bottom product. If these specifications are to be met at minimum operating costs and at maximum utilization of the column, corrective actions must be taken at the proper time and rate to minimize the effects of disturbances on product compositions and flows.

The operation of such a distillation column is affected by disturbances in independent input variables (i.e., variables which can change or be changed independently without any effect of one upon the other). Such independent variables can either be manipulated or are uncontrolled. Feed composition and feed flow are examples of independent input variables which often cannot be altered or controlled (within the limits of the process in question). Reboiler steam flow and distillate product flow are examples of manipulated or controlled independent input variables. Then there are dependent output variables, such as the purities of the distillate and bottom products, which are a function or result of the independent variables. As should be evident, a distillation column has numerous degrees of freedom and any significant step in the control of the operation of a distillation column must reduce these degrees of freedom.

The degrees of freedom of the distillation column of FIGURE 1 can be reduced by providing it with minimum controls well known in the art. Referring now to the drawing, a constant pressure in the top of column 11 can be maintained by an assembly comprising a pressure transducer 38 and pressure controller 39 in conjunction with control valve 26. A constant pressure can be maintained in accumulator 28 by passing a small amount of overhead from line 24 to accumulator 28 via by-pass line 41, the constant pressure being provided by assembly comprising pressure transducer 42, pressure controller 43 and flow control valve 44. The flow rate in distillate product line 33 can be controlled by an assembly comprising orifice plate 45, differential pressure transducer 46 and flow controller 47 in conjunction with control valve 34, flow controller 47 being manipulated or cascaded by a liquid level controller 48 associated with accumulator 28, so as to maintain a constant liquid level in the accumulator. The volume flow rate of steam in line 17 can be controlled by an assembly comprising orifice plate 51, differential pressure transducer 52 and flow controller 53 in conjunction with flow control valve 18. The volume flow rate of steam in line 19 can be controlled by an assembly comprising

orifice plate 54, differential pressure transducer 56 and flow controller 57 in conjunction with flow control valve 23. The flow rate of bottom product in line 36 can be controlled by an assembly comprising orifice plate 58, differential pressure transducer 59 and flow controller 61 in conjunction with control valve 37. Similarly, the flow rate of feed in line 12 can be manipulated by an assembly comprising orifice plate 62, differential pressure transducer 63 and flow controller 64 in conjunction with flow control valve 13, the setpoint of the flow controller usually being adjusted to satisfy the inventory requirements of the upstream processes. Further reduction in the degrees of freedom in the column can be accomplished by using the level of liquid in the reboiler of column 11 to manipulate the volume of steam passed via line 19 to the reboiler. This can be done by an assembly comprising a liquid level controller 65 which manipulates the setpoint of flow controller 57. The use of these minimum control features of the prior art reduces the number of the degrees of freedom of the column. However, many input variables can still affect the operation.

An input variable of primary concern in one aspect of this invention is feed tray location. Material changes in feed composition and/or product specifications, which changes can affect operation costs by reason of their effects on the liquid-vapor mass transfer taking place in the column, are taken into consideration according to this invention and the optimum feed tray necessary to fractionate the feedstock, notwithstanding such changes, is automatically determined by this invention so as to minimize column heat input. The feed tray location accordingly can be automatically manipulated, i.e. the introduction of feed onto one of several trays is controlled in an automatic manner in accordance with the determined optimum feed tray. There will now be described, how, according to this invention, the optimum feed tray is determined how the feed tray location can be accordingly manipulated so that products, such as distillate and bottom products, with specified purities can be produced at minimum heat input to the column.

In one aspect of this invention, the optimum feed tray location is determined by taking the partial derivative of a predictive, statistically-derived equation, with respect to feed tray, setting the partial derivative equation equal to zero and then solving it for the optimum feed tray location. The statistically-derived equation can be that for predicting internal reflux flow or heat supplied to the column (either total heat or just reboiler heat) since internal reflux flow will be proportional to heat input. By taking the partial derivative of the statistically-derived equation in this manner, the heat input of the column, e.g., reboiler heat, is minimized.

The internal reflux flow rate can be found according to that disclosed and claimed in copending application Ser. No. 189,375, filed Apr. 23, 1962, now Patent No. 3,296,097, by D. E. Lupfer. Briefly, measurements are made of feed flow rate and the amounts of components in the feedstock, signals representing such measurements are combined with other signals representing certain constants in a statistically-derived equation based on the expression:

$$R_{IP} = f(F, F_c, E, F_T, F_e, H_D, L_B) \quad (1)$$

where:

R_{IP} = predicted internal reflux flow rate (vol./unit time)

F = feed flow rate (vol./unit time)

F_c = generic symbol for the components in feed, each expressed as a liquid volume fraction of feed

E = average column tray efficiency

F_e = feed enthalpy (B.t.u./lb.)

F_T = feed tray (numbering trays from top of column)

H_D = specified liquid volume fraction of heavy key in distillate product

L_B = specified liquid volume fraction of light key in bottom product

The exact equation used to predict what the internal reflux flow rate of the distillation column should be to obtain a specified separation will vary. But, having determined what independent variables are significantly related to internal reflux, it is possible by straight-forward, well-known statistical methodology to determine how these significant variables can be combined in an equation to predict internal reflux flow rate with specified limits of accuracy to compensate for changes in feed composition and feed flow.

The following summarizes the statistical approach in deriving a predictive equation for internal reflux;

(1) Select all independent variables believed to exert a significant effect upon internal reflux;

(2) Design and carry out screening experiments to test for the significant effects of the independent variables;

(3) Perform a correlation analysis to identify variables which should be represented in a predictive equation;

(4) Perform a surface response experiment either on the actual operating column or by tray-to-tray calculations (e.g., on a digital computer) to obtain data, using a suitable experimental design for data gathering, such as the Box-Wilson composite design; and

(5) Using regression analysis, determine the best set of coefficients for an assumed form of the predictive equation and determine the precision of the equation in terms of coefficient of determination and standard error of estimate.

Those skilled in the art of statistics will be able to determine the predictive equation for internal reflux for any distillation column, in view of the foregoing discussion

As an example, the distillation column 11 of FIGURE 1 is used as a debutanizer to separate a mixture of hydrocarbons to produce a distillate product comprising isopentane (iC_5), normal butane (nC_4), isobutane (iC_4), and propane (C_3), and a bottom product comprising normal butane (nC_4), isopentane (iC_5), normal pentane (nC_5) and some components heavier than nC_5 designated C_6+ . Isopentane (iC_5) is the heavy key component and appears as an impurity in the distillate product, while normal butane (nC_4) is the light key component and appears as an impurity in the bottom product.

The data of Table I is representative of the statistical designed experiment that was necessary to describe the surface response of column 11.

TABLE I

Run	Feed components (liquid volume percent)			Product specifications (liquid volume percent)		E	F_e^*	$F_T^\dagger$	R_{IP}/F	$H_R^\ddagger$
	C_3+iC_4	nC_4	iC_5	L_B	H_D					
1	37.0	30.5	13.0	1.0	0.2	74	11	19	1.028	125.3
2	26.0	25.5	13.0	1.0	0.4	74	25	31	0.844	120.7
3	37.0	25.5	9.0	1.0	0.4	74	11	19	0.724	103.7
4	26.0	30.5	13.0	0.4	0.4	60	25	31	1.454	182.3
5	26.0	25.5	9.0	1.0	0.4	60	25	31	0.825	131.5
6	37.0	25.5	13.0	0.4	0.4	74	25	19	0.884	97.5
7	26.0	30.5	9.0	0.4	0.4	74	25	31	0.861	131.3
8	37.0	30.5	9.0	0.4	0.4	60	11	19	0.906	122.2
9	31.5	23.0	11.0	0.7	0.3	67	18	25	0.759	111.8
10	20.5	28.0	11.0	0.7	0.3	67	18	25	0.827	143.8
11	42.5	28.0	11.0	0.7	0.3	67	18	25	0.864	90
12	31.5	28.0	11.0	0.7	0.3	67	4	25	0.816	128.3
13	31.5	28.0	11.0	0.7	0.3	67	32	25	0.875	107.4
14	31.5	28.0	11.0	0.2	0.3	67	18	25	1.036	142.5

*Reference temp. 151° F.

†Trays numbered from top of column.

‡Reboiler heat.

Eighty-one runs were actually used to describe the surface and the runs in Table I are typical. The data for this experiment were obtained by tray-to-tray calculations on an I.B.M. 7090 digital computer. It is also possible to obtain the data from an actual operating column. However, this presents many problems, chief among

which is that the variables usually do not change or cannot be changed over the range necessary to complete the statistically designed experiment. The internal reflux flow rate was defined by the following expression:

$$R_{IP}=f(C_3, iC_4, nC_4, iC_5, nC_5, F, F_T, F_e, H_D, L_B) \quad (2)$$

where:

R_{IP} =predicted internal reflux flow rate (vol./unit time)

C_3 =liquid volume fraction of propane in feed

iC_4 =liquid volume fraction of isobutane in feed

nC_4 =liquid volume fraction of normal butane in feed

iC_5 =liquid volume fraction of isopentane in feed

nC_5 =liquid volume fraction of normal pentane in feed

F =feed flow rate (vol./unit time)

F_T =feed tray location (trays numbered from top to column)

F_e =feed enthalpy (B.t.u./lb.)

H_D =specified liquid volume fraction of isopentane desired in distillate

L_B =specified liquid volume fraction of normal butane desired in bottom product

As pointed out in said copending application Ser. No. 189,375, expression (2) can be simplified and developed for the ratio of R_{IP} to F :

$$\frac{R_{IP}}{F}=f[(C_3+iC_4), nC_4, iC_5], E, F_T, F_e, H_D, L_B] \quad (3)$$

Based on data such as shown in Table I and Equation 3, the following predictive statistically-derived equation was developed:

$$\frac{R_{IP}}{F}=K_1+iC_5[K_2+K_3(nC_4)+K_4(iC_5)+K_5(C_3+iC_4)]+K_6(C_3+iC_4) \quad (4)$$

where:

$$K_1=A_1+A_2(F_T)^2+A_3(E)+A_4(E)^2+A_{23}(F_e)^2+$$

$$H_D[A_9+A_{10}(H_D)+A_{11}(L_B)+A_{12}(E)]+$$

$$L_B[A_5(L_B)+A_6(E)+A_7+A_8(F_T)]$$

$$K_2=A_{13}(L_B)+A_{14}(E)(H_D)+A_{15}(E)+$$

$$A_{17}(H_D)+A_{16}(E)(F_T)$$

$$K_3=A_{18}+A_{19}(E)$$

$$K_4=A_{20}$$

$$K_5=A_{21}(E)$$

$$K_6=A_{22}(F_e)$$

$$A_1 \text{ through } A_{23}=\text{constants}$$

According to one aspect of this invention, as mentioned above, the partial derivative of Equation 4 is taken with respect to F_T , thus:

$$\frac{\partial R_{IP}}{\partial F_T} = 2A_2(F_T) + A_8(L_B) + A_{16}(E)(iC_5) \quad (5)$$

By setting Equation 5 equal to zero and solving it for the optimum feed tray, F_{T_0} , the following equation for the optimum feed tray for the particular column described is found:

$$F_{T_0} = -\frac{A_8(L_B) + A_{16}(E)(iC_5)}{2A_2} \quad (6)$$

or

$$F_{T_0} = K_7 + K_8(iC_5) \quad (7)$$

where:

$$K_7 = -\frac{A_8(L_B)}{2A_2}$$

$$K_8 = -\frac{A_{16}(E)}{2A_2}$$

The particular equation for optimum feed tray will, of course, vary with different distillation columns and feed compositions, but generally the optimum feed tray equation will necessitate for its solution the production of signals representative of the relative amounts of at least one feed component in the feedstock and the heavy key component in the distillate and/or light key component in the bottom product, which signals are combined in the manner dictated by the particular optimum feed tray equation.

Referring again to FIGURE 1, I have designated as 66 a computer which can be used to automatically solve Equation 7 for the optimum feed tray, F_{T_0} . The feed composition information needed in the solution of Equation 7 is provided by an analyzer 67, the latter being in communication with a feed line 12 by reason of a sample line 68. Analyzer 67 comprises any suitable instrument which continuously or substantially continuously (i.e., rapid cycle) analyzes the feed and determines the relative amounts, e.g., liquid volume percent, of the components in the feed which function as independent variables in the predictive equation, and produces signals proportional thereto. Analyzer 67, such as described in I.S.A. Journal, vol. 5, No. 10, p. 28, October 1958, preferably comprises a high speed chromatographic analyzer having a sampling valve, motor, detector, chromatographic column, programmer, and a peak reader, the latter functioning to read the peak height of the components, giving an equivalent output signal which is suitable for control purposes. In operation, sample flows continuously through the analyzer. At a signal from the programmer, a measured volume of sample is flushed into the chromatographic column. When a sample component arrives at the detector, the resulting signal is measured, amplified, and stored until the next signal when the sequence is repeated. The stored signal is a continuous output signal analogous to the amount of the component present. Such an analyzer and the operation thereof are well known in the art.

A signal 69 proportional to iC_5 (the liquid volume fraction of isopentane in the feed), necessary for the solution of Equation 7, is transmitted to predictive feed tray computer 66. The output signal from computer 66 can be transmitted via signal line 71 to a suitable feed tray selector 72 which is designed to manipulate the flow control valves in feed tray supply lines 12a, 12b and 12c, so as to introduce the feed 12 onto the so-determined optimum feed tray of column 11.

Referring now to FIGURE 2 in detail, wherein mathematical analog instrumentation for solution of Equation 7 is shown, a reference potential 73 is applied across a

potentiometer K_7 and the output signal therefrom transmitted to a summing relay or adder 74. Signal 69, representing iC_5 , is applied across a potentiometer K_8 , and the resulting product signal $K_8(iC_5)$ is also transmitted to summing relay 74. The sum signal 71 from relay 74, representing optimum feed tray F_{T_0} , is produced and it can be recorded by a recorder (not shown) and used for monitoring purposes only, but preferably said signal is sent forward to the tray selector 72 of FIGURE 1 for automatic manipulation of the feed tray location.

In FIGURE 3, I have illustrated a suitable tray selector to manipulate the feed supply and pass it to the determined optimum feed tray, and it comprises voltage comparators 76, 77 and relay switches 78, 79. Feed tray supply lines 12a, 12b and 12c are shown, each having flow control valves therein, such valves being normally closed air-operated diaphragm valves, controlled by the selector, which in turn is manipulated by signal 71 from computer 66.

V_a is a voltage representing the tray number midway between the trays supplied by supply lines 12c and 12b, and V_b is a voltage representing the tray number midway between the trays supplied by supply lines 12a and 12b. Each of voltage comparators 76 and 77 have two inputs I_1 and I_2 , as shown. These voltage comparators are energized when I_1 (corresponding to F_{T_0}) is greater than I_2 (i.e., when F_{T_0} is greater than V_a and V_b). Relays 78 and 79 each comprise a pivotal contact 81, 82, respectively, which is normally biased in an "up" position by a spring (but shown in the drawing in their "neutral" position), and a rod connected to the contact at one end is surrounded by an electrical coil at the other end, said coil being energized by its adjacent voltage comparator. The boxes containing "I/P" in FIGURE 3 are conventional current-to-pressure converters.

In operation, when F_{T_0} is less than either of V_a or V_b , the voltage comparators are not energized and the ends of both relays will be in their "up" positions, and the valve in supply line 12c will be open, while the valves in supply line 12b and 12a will be closed. When F_{T_0} is greater than V_a but less than V_b , only voltage comparator 76 will be energized, and relay 78 will be in its "down" position and relay 79 will be in its "up" position and consequently only the valve in supply line 12b will be opened. When F_{T_0} is greater than either V_a or V_b , both voltage comparators will be energized and both relays will be in their "down" positions, and consequently the valve on supply line 12a will be opened. Similar tray selectors can be designed for any number of feed trays.

In another aspect of this invention, the optimum feed tray is determined by taking the partial derivative of a predictive statistically-derived equation for the heat supplied to the distillation column, with respect to feed tray, setting it equal to zero and solving for the optimum feed enthalpy. Depending on the particular column, the physical state of the feedstock introduced into the column, and the operation thereof, this heat input will be either the sum of the heat content (enthalpy) of the feedstock plus the heat added to the column by the reboiler, or the total heat will be in effect the same as that of the reboiler heat alone. In any case the predictive statistically-derived equation for total heat can be derived by the same statistical approach used in deriving the predictive equation for internal reflux.

Again assuming that the distillation column 11 of FIGURE 1 is used as a debutanizer to separate said mixture of hydrocarbons the data of Table I can be used to develop the total heat according to the expression

$$H_T = f(F, F_e, E, F_T, F_c, H_D, L_B) \quad (8)$$

where:

H_T = predicted heat input supplied to the column (B.t.u./lb. of feed)

F = feed flow rate (vol./unit time)

F_c =generic symbol for components in feed, each expressed as a liquid volume fraction of feed

E =average column tray efficiency

F_e =feed enthalpy (B.t.u./lb. of feed)

F_T =feed tray (numbering trays from top of column)

H_D =specified liquid volume fraction of heavy key component in distillate product

L_B =specified liquid volume fraction of light key component in bottom product

Expression (8) can be rewritten as follows for the debutanizer column example set forth above:

$$H_T = f(C_3, iC_4, nC_4, iC_5, nC_5, F, E, F_T, E_e, F_e, H_D, L_B) \quad (9)$$

where:

C_3 =liquid volume fraction of propane in feed

iC_4 =liquid volume fraction of isobutane in feed

nC_4 =liquid volume fraction of normal butane in feed

iC_5 =liquid volume fraction of isopentane in feed

nC_5 =liquid volume fraction of normal pentane in feed

H_D =specified liquid volume fraction of isopentane desired in distillate

L_B =specified liquid volume fraction of normal butane desired in bottom product

As mentioned above total heat input (H_T) can be either the sum of the heat content of the feedstock plus the heat added by the reboiler, or can be equal to the reboiler heat only, depending upon the particular distillation column, physical state of the feed, and etc. For the particular example under consideration, namely where the column 11 of FIGURE 1 is used as a debutanizer column, the total heat will be the sum of the feed heat content and reboiler heat. Based on the data of Table I and expression (9), the following predictive statistically-derived equation for total heat was developed:

$$H_T = B_1 + \frac{R_{Tp}}{F} [B_2 + B_3(C_3 + iC_4) + B_4(iC_5)] + B_5(C_3 + iC_4) + B_6(nC_4)(iC_5) \quad (10)$$

where B_1 through B_6 are all constants and R_{Tp}/F is as defined in Equation 7.

By taking the partial derivative of Equation 10 with respect to feed tray location F_T , we have:

$$\frac{\partial H_T}{\partial F_T} = \frac{\partial R_{Tp}}{\partial F_T} [B_2 + B_3(C_3 + iC_4) + B_4(iC_5)] \quad (11)$$

By setting Equation 11 equal to zero, one solution is:

$$B_2 + B_3(C_3 + iC_4) + B_4(iC_5) = 0 \quad (12)$$

Equation 11 cannot be solved for F_T because it does not contain this term. Therefore, the other solution to Equation 10 is:

$$\frac{\partial R_{Tp}}{\partial F_T} = 0 \quad (13)$$

Equation 13 is the same as Equation 5 when it is set equal to zero. Thus, in this particular example where column 11 is a debutanizer for fractionating the said mixture of hydrocarbons, the optimum feed tray, F_{To} will be the same whether one takes the partial derivative of the predicted reflux flow rate-to-feed flow rate ratio or by taking the partial derivative of total heat, with respect to feed tray location.

In another aspect of this invention an input variable of primary concern is that of feed enthalpy. Material changes in the feed composition or feed flow can also effect the purity of the products and operation costs by reason of the affects of such changes on the liquid-vapor mass transfer taking place in the column. According to this aspect of the invention, the optimum feed enthalpy can be continuously determined, while minimizing heat input, and

this determined value used in controlling the heating of the feedstock. As with the case of finding the optimum feed tray location, the optimum feed enthalpy value is similarly found by taking the partial derivative of either the statistically predicted internal reflux flow rate-to-feed flow rate ratio (or simply internal reflux), with respect to feed enthalpy, or by taking the partial derivative of the statistically-derived equation for total heat, with respect to feed enthalpy. Such partial derivative equation is set equal to zero and the value for the optimum feed enthalpy F_{eo} is thus found.

Again using as an example the debutanizer column described above, the partial derivative of Equation 4 can be taken with respect to feed enthalpy; thus:

$$\frac{\partial R_{Tp}}{\partial F_e} = 2A_{23}(F_e) + A_{22}(C_3 + iC_4) \quad (14)$$

By setting Equation 14 equal to zero and solving for the optimum feed enthalpy, we have:

$$F_{eo} = -\frac{A_{22}}{2A_{23}}(C_3 + iC_4) \quad (15)$$

Equation 15 can be simplified:

$$F_{eo} = K_9(C_3 + iC_4) \quad (16)$$

where:

$$K_9 = -\frac{A_{22}}{2A_{23}}$$

The particular equation for optimum feed enthalpy will, of course, vary with different columns and feed compositions, but generally the optimum feed enthalpy equation will necessitate for its solution the production of signals representative of the relative amount of at least one feed component in the feedstock which signal will be combined in the manner dictated by the particular optimum feed enthalpy equation.

FIGURE 1 illustrates a predictive feed enthalpy computer 84 which solves Equation 16 and one embodiment of mathematical analog instrumentation that can be used to continuously solve for the optimum feed enthalpy value F_{eo} of Equation 16 is shown in FIGURE 4, where signal 85, representing the sum of C_3 and iC_4 (as produced by analyzer 67 of FIGURE 1) is multiplied by K_9 , which can be a potentiometer or the like, to produce a signal 86 representing the optimum feed enthalpy F_{eo} . This latter value can be transmitted to a recorder (not shown) and used for monitoring purposes only, but preferably is transmitted, as shown in FIGURE 1, to an enthalpy controller 87, to which is also supplied a signal 88 representing the actual or measured feed enthalpy. Enthalpy controller 87 compares signals 86 and 88 and accordingly manipulates the setpoint of steam flow controller 53 so as to maintain the enthalpy of the feed introduced into the column 11 at the predicted optimum feed enthalpy value. In the event that the measured or actual feed enthalpy signal 88 is smaller in magnitude than the predicted optimum feed enthalpy 86, flow controller 53 will accordingly open the flow control valve 18 so as to add more heat to the feed flowing through line 12 in indirect heat exchange with preheater 16. Conversely, if the actual or measured feed enthalpy signal 88 is greater in magnitude than the optimum feed signal 88, steam flow controller 53 will accordingly manipulate valve 18 by closing down the same to decrease the heat supplied to the feed 12 by preheater 16.

The actual or measured feed enthalpy value 88 can be computed by computer 89 according to that disclosed and claimed in copending application Ser. No. 125,025, filed July 3, 1961, by M. W. Oglesby, Jr., et al., and now U.S. Patent No. 3,269,921. Where the feed at the exit of economizer 14 is partially vaporized, the actual feed enthalpy

of the feed introduced into the distillation column of FIGURE 1 can be found by solution of the equation:

$$F_{em} = C_{pF}(T_1 - T_o) + (F_S/F_F)(h_s) + (F_B/F_F)(C_{pB})(T_{B1} - T_{B2}) \quad (17)$$

where:

F_{em} = measured enthalpy of the feed referenced to T_o (B.t.u./lb. of feed)

$C_{pF}(T_1 - T_o)$ = initial enthalpy of feed (B.t.u./lb. of feed)
 $(F_B/F_F)(C_{pB})(T_{B1} - T_{B2})$ = enthalpy given to the feed in the economizer exchanger (B.t.u./lb. of feed)

C_{pF} = average specific heat of feed (B.t.u./lb. $\times$ $^{\circ}$ F.)

T_1 = temperature of feed before entering economizer exchanger ($^{\circ}$ F.)

F_S = steam flow (lb./hr.)

F_F = feed flow (lb./hr.)

F_B = bottoms product flow (lb./hr.)

h_s = difference in enthalpy of steam entering preheater and the condensate (B.t.u./lb. of steam)

C_{pB} = average specific heat of bottoms product (B.t.u./lb. $\times$ $^{\circ}$ F.)

T_{B1} = temperature of bottoms product entering economizer exchanger ($^{\circ}$ F.)

T_{B2} = temperature of bottoms product leaving economizer exchanger ($^{\circ}$ F.)

T_o = arbitrary reference temperature used to compute F_{em} ($^{\circ}$ F.)

Referring again to FIGURE 1, signals proportional the squares of the flow rates of steam in line 17, feed in line 12, and bottom product in line 36, as established by differential pressure transducers 52, 63 and 59, respectively, and transmitted to the actual feed enthalpy computer 89 for solution of Equation 17. Temperature transmitters 91, 92 and 93 can be provided to provide the temperatures T_1 , T_{B1} , T_{B2} of Equation 17, and these signals can also be transmitted to computer 89. In the interest of brevity, no further discussion will be made here of the computation or measurement of actual feed enthalpy, since the same is adequately disclosed in said copending application 125,025, now U.S. Patent No. 3,269,921, and reference should be made thereto.

The optimum feed enthalpy F_{eo} , like that of the optimum feed tray location F_{To} , can also be found by taking the partial derivative of the statistically-derived equation for total heat with respect to feed enthalpy, setting this partial derivative equation equal to zero, and solving it for optimum feed enthalpy. The value or equation obtained for optimum feed enthalpy value will be the same as that of Equation 15.

While it is within the scope of this invention to derive either one of optimum feed tray location F_{To} , or optimum feed enthalpy F_{eo} , so as to minimize the heat input required by the column to effect the desired fractionation of the feedstock to produce desired products, I prefer to derive both F_{To} and F_{eo} , and thereby obtain the minimum column heat input necessary to effect the operation desired.

In another aspect of this invention, I propose to manipulate feed tray location and feed enthalpy in conjunction with the manipulation of reflux flow rate in the predictive manner disclosed in copending application Ser. No. 189,375, now U.S. Patent No. 3,296,097, filed Apr. 17, 1962, by D. E. Lupfer. In said copending application Ser. No. 189,375, now U.S. Patent No. 3,296,097, measurements are made of the flow rate of feedstock to the column and concentrations of components in said feedstock, signals are produced proportional to such measurements and combined with other signals proportional to constants in a statistically-derived equation to predict internal reflux flow rate of such a column, a signal is produced proportional thereto, and the external reflux flow rate is manipulated to maintain the predicted internal reflux flow rate value. Further, I also prefer to manipulate these variables in conjunction with the manipulation of bottom

product flow rate in the manner disclosed in copending application Ser. No. 118,066, filed June 19, 1961, by D. E. Lupfer, now U.S. Patent No. 3,224,947. In said copending application Ser. No. 118,066, now U.S. Patent No. 3,224,947, measurements are made of the flow rate of the feed and components in the feed, signals are produced proportional thereto, and these signals combine with another signal representing the rate at which the bottom product should be withdrawn from the column to make a preselected separation between components of the feed, and the flow rate of the bottom product controlled accordingly.

In FIGURE 1, I have generally designated as 101 an "operations computer," which is intended to include the reflux computer and bottom product flow computer means disclosed in said copending applications Ser. Nos. 189,375, now U.S. Patent No. 3,296,097, and 118,066, now U.S. Patent No. 3,224,947, respectively. In predicting the internal reflux according to said copending application Ser. No. 189,375, now U.S. Patent No. 3,296,097, it is necessary to employ values representative of average tray efficiency E , feed tray location F_T , feed enthalpy F_e , specified liquid volume fraction (L_B) of the light key in the bottom component, and specified liquid volume fraction (H_D) of the heavy key in the distillate, and I have illustrated in FIGURE 1 the introduction of input signals representing these values to the operations computer 101, with values for F_T and F_e being supplied by computers 66 and 84, respectively.

Operations computer 101 produces an output signal 102, proportional to the predicted internal reflux flow rate, and this value is used as a setpoint-adjusting signal for the flow controller 35 in the external reflux line 31, so as to maintain the predicted internal reflux. Operations computer 101 also produces an output signal 105 proportional to the predicted bottom product flow rate, and this signal is transmitted to a biasing relay 106 (e.g. summing relay) which produces an output signal 108 that serves as a setpoint for flow controller 61 on bottom product line 36. Copending application Ser. No. 189,375, now U.S. Patent No. 3,296,097, discloses that the manipulation of bottom product can be cascaded with suitable feedback control since the predictive control of internal reflux may often only be approximate and not exact, as is the case with many predictive controls. Thus, to achieve this feedback control, referring again to FIGURE 1, the overhead in line 24 is analyzed by means of analyzer 116 to determine the concentration of heavy key component, e.g., isopentane. Analyzer 116 can be a chromatographic, infrared, or ultraviolet analyzer, or the like, or a mass spectrometer, or any other suitable analyzer which will measure the concentration of the component and provide a signal representative thereof. Analyzer 116 produces an output signal corresponding to the concentration of the heavy key in overhead line 24 and it is transmitted to a controller 117, such as an analyzer recorder controller, where it is compared with a setpoint signal 118 proportional to H_D . Any difference between the actual or measured heavy key concentration in the overhead and H_D is transmitted as a signal to bias relay 106. For example, if the key component in the bottom product is on specification, but the key component in the overhead is less than the specified concentration H_D , this means that the overhead (and consequently the distillate) has a purity greater than that necessary, i.e., that the column is being operated at operating costs greater than the minimum. Accordingly, the analyzer controller 117 produces a signal 119 which can add to or subtract from the computed bottom flow signal 105. If computed bottom flow signal 105 is exactly that required to give the distillate product purity specified, signal 108 will equal signal 105. Due to errors in measurements and computing, signal 105 will be slightly altered by signal 119 to always produce the exact bottom flow setpoint 108 required.

Where the bottom product purity is of more importance than the distillate purity, analyzer means can analyze instead the bottom product to determine the concentration of the light key component therein, and the difference between this measurement and L_B can be used to bias the computed bottom flow signal 105.

Various modifications and alterations of this invention will become apparent to those skilled in the art without departing from the scope and spirit of this invention, and it should be understood that this invention is not to be limited unduly to that set forth herein for illustrative purposes.

What is claimed is:

1. In a process wherein a multicomponent feed stream is heated and introduced into a distillation column for separation therein into a distillate product stream and a bottom product stream each of which possess a specified purity, a column overhead vapor stream is produced and at least partially condensed, some of said condensed overhead is recycled to said column as an external reflux stream, of said column overhead stream is yielded as a distillate product stream having a specified purity, wherein heat is supplied to said column to effect said separation, an improved control method for determining the optimum enthalpy of the heated feed stream introduced into said column necessary to produce said product purities while minimizing the input of heat to said column, said method comprising the steps of measuring a process variable indicative of the flow rate of feed to said column; producing a signal representative of the flow rate of feed to said column; analyzing said feed to determine the concentrations of components present in said feed; producing signals representative of the concentrations of said components in said feed; combining said signals in an operations computer in a manner based on the following expression:

$$X=f(F, F_c, E, F_T, F_e, H_D, L_B)$$

where:

X =predicted value for one of column reflux flow rate and heat input rate,

F =flow rate of said feed stream,

F_c =generic symbol for the concentrations of said feed components expressed as liquid volume fractions of said feed stream,

E =tray efficiency of said column,

F_T =feed tray of said column, numbering trays from the top of said column,

F_e =enthalpy of said feed stream,

H_D =specified liquid volume fraction of heavy key component in said distillate product stream,

L_B =specified liquid volume fraction of light key component in said bottom product stream;

producing in a predictive feed enthalpy computer a signal representative of the optimum feed enthalpy based on the following expression:

$$\frac{\partial X}{\partial F_e}=0$$

wherein:

X =predicted value for one of column reflux flow rate and heat input rate,

F =feed flow rate,

F_e =enthalpy of said feed stream;

measuring process variables indicative of the feed enthalpy; producing a signal representative of the actual enthalpy of the feed entering the column; comparing in an enthalpy controller said signal representing the predicted feed enthalpy and said signal representing the actual feed enthalpy; controlling in response to said difference the

flow rate of a preheater heat supply stream; controlling from said predicted value X the flow rate of a stream selected from the group consisting of the external reflux stream, and the reboiler heat supply stream in order to operate the distillation column to maintain specified product purities at minimum total heat input to said column with respect to feed enthalpy.

2. A process according to claim 1 including the steps of analyzing one of said streams from the group consisting of the bottom product stream and the distillate product stream; producing a signal responsive to the concentration of a specified key component in said stream; producing in said operations computer a signal representative of a desired terminal product stream flow rate; and biasing said signal from the operations computer with said signal responsive to the concentration of said key component in said stream that is measured.

3. In a process wherein a multicomponent feed stream is introduced onto one of several trays in a fractional distillation column and separated therein into a distillate product stream and a bottom product stream each of which possesses a specified purity, a column overhead vapor stream is produced and at least partially condensed, some of said condensed overhead is recycled to said column as an external reflux stream, some of said column overhead stream is yielded as a distillate product stream having a specified purity, wherein heat is supplied to said column to effect said separation, a control method for determining which of several trays is the optimum feed tray necessary to introduce said feed stream into said column to produce said product streams with said purities while minimizing the input of said heat to said column, said method comprising the steps of measuring process variables indicative of the flow rate of feed to said column; producing a signal representative of the flow rate of feed to said column; analyzing said feed stream to determine the concentrations of components present in said feed stream; producing signals representative of the concentrations of at least one component in said feed stream; combining said signals in a manner based on the following expression in an operations computer:

$$X=f(F, F_c, E, F_T, F_e, H_D, L_B)$$

where:

X =predicted value for one of column reflux flow rate and heat input rate,

F =flow rate of said feed stream,

F_c =generic symbol for the concentrations of said feed components expressed as liquid volume fractions of said feed stream,

E =tray efficiency of said column,

F_T =feed tray of said column, numbering trays from the top of said column,

F_e =enthalpy of said feed stream,

H_D =specified liquid fraction of heavy key component in said distillate product stream,

L_B =specified fraction of light key component in said bottom product stream;

producing a signal representative of X ; producing in a predictive feed tray computer a signal representative of the optimum feed tray location based on the following expression:

$$\frac{\partial X}{\partial F_T}=0$$

wherein:

X =predicted value for one of column reflux flow rate and heat input rate,

F =feed flow rate,

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F_T =feed tray, numbering from the top of the column; controlling in response to said signal the location in said column to which said feed stream is introduced, and controlling responsive to said X value the flow rate of one of said streams selected from the group consisting of an external reflux stream, and a reboiler heat supply stream in order to produce product streams of specified purities at minimum total heat input to said column, with respect to feed tray location.

4. A process according to claim 3, further including the step of analyzing at least one of said streams selected from the group consisting of the bottom product stream and the distillate product stream to determine the concentration of a specified key component therein; producing a signal responsive to the concentration of a specified key component in said analyzed stream; producing in said operations computer a signal representative of a desired terminal product stream flow rate and biasing said flow rate signal with the signal responsive to the concentration of said key component in said stream that is measured.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,356,590

December 5, 1967

Merion L. Johnson

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 13, line 21, "of said column" should read -- some of said column --.

Signed and sealed this 14th day of October 1969.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

WILLIAM E. SCHUYLER, JR.

Commissioner of Patents