Condensation enhancement by steam pulsation in a reflux condenser

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Reflux condensation in a long vertical tube was experimentally investigated for both the case in which the inlet mass flow rate was steady and the case in which steady controlled pulsation was applied to the inlet steam flow. The steam flow rate and heat removal capability of the condenser under steady inlet steam flow were found to be severely limited by the formation of a plug of single-phase condensate on top of the two-phase condensing region, as a result of flooding in the tube. Subsequently, steady controlled pulsations were applied to the inlet steam flow with the aim of preventing the formation of a stable water column above the condensing region. Three pulsing frequencies, 0.08 Hz, 0.14 Hz, and 0.25 Hz, were considered. The controlled pulsations were found to have a destabilizing effect on the water column, and led to several-fold increase in the condensation capacity and heat removal rates in the condenser. Further, this improvement in performance was dependent on the frequency of pulsation. An analytical model for the limiting process of countercurrent steam and subcooled-condensate flow, or flooding, which took into account the additional steam condensation effects resulting from the subcooled condensate, was compared with the experimental data. The theoretical model revealed that flooding will exhibit a hysteresis effect above a certain level of subcooling, a characteristic feature of steady inlet flow reflux condensation that was also observed experimentally.

Keywords: condensation; reflux condenser; partial condenser; flow pulsation

Introduction

When a vapor flows through a vertical pipe with a wall temperature maintained lower than the saturation temperature corresponding to the pressure of the vapor, part or all of the vapor, depending on the prevalent flow conditions, will condense, producing a film of condensate flowing downward countercurrent to the vapor flow. This is the basic process in industrial reflux condensers.

Of particular importance in the reflux condensation phenomenon and reflux condenser applications is the capacity limitation because of flooding. The phenomenon that occurs in a single vertical tube reflux condenser when the inlet vapor flow is kept steady may be described as follows.

At very low vapor mass flow rates all the injected vapor is condensed in a short length of the tube, and a wavy condensate film will flow downward by gravity, countercurrent to the rising vapor. When the mass flow rate is increased beyond this low range, flooding, describing the phenomenon under which the upward vapor flow prevents the downward flow of most of the condensate, will occur in the tube. The condensate thus builds up above the condensing region and is periodically carried over to the tube exit. The establishment and growth of the single-phase condensate column is usually accompanied by a sudden and monotonic rise in the pressure drop across the tube (Kent and Pigford 1956; Kutateladze 1972; Liu and Collier 1980; Mandl and Weiss 1982; Nguyen and Banerjee 1982). The pressure drop decreases significantly each time the condensate column is carried over. Thereafter the condensate column is reestablished, resulting in a cycle operation with wide variations in the operating pressure. Beyond the range of this carry-over operation, two-phase climbing-film flow, with totally concurrent flow of the condensate and the vapor, will be established in the tube, and all the condensate will be blown out of the tube (Butterword 1973).

The flooding limitation on the condensation capacity constitutes the major disadvantage of partial condensers in large-scale chemical distillation processes, and thus the research and development of this equipment has been very limited. Recently, however, in a related application, the reflux condensation phenomenon has been the subject of renewed interest because of its importance in certain abnormal operations of nuclear power plants (Mandl and Weiss 1982; Nguyen and Banerjee 1982; Obinelo 1990; Russell 1980). These recent investigations on the reflux condensation phenomenon have been largely concentrated on the parametric dependence of its heat removal capacity.

Russell (1980) studied the condensation process in a long reflux tube (l/d ratio 250) inclined at 57° and observed that above a certain inlet steam flow rate total reflux condensation ensued, with a single-phase condensate column above the condensing region. At higher flow rates a cyclic carry-over mode of operation occurred.

Calia and Griffith (1982) studied the flow patterns in a four-inverted U-tube array and reported successive blockage of the tubes by single phase water columns, which led to a cyclic fill-and-dump operation with a high system pressure drop.

Banerjee et al. (1983) conducted a detailed investigation of reflux condensation in a single long vertical tube and reported that flooding at the tube inlet led to the formation of a liquid

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column above the two-phase condensing region, which in turn substantially increased the system pressure drop and limited the amount of steam that could be condensed.

Chang et al. (1985) studied complete reflux condensation in four- and eleven-tube banks and reported cyclic fill-and-dump operation due to liquid-column blockage of the tubes.

In this study, reflux condensation of steam in a long vertical tube reflux condenser was extensively investigated. Of particular interest was possible means of capacity and heat removal enhancement by destabilization of the condensate column formed as a result of flooding in the tube. In this regard, controlled pulsations were applied to the steam flow into the reflux condenser.

Experimental setup and procedure

The reflux condenser used in this study is depicted in Figure 1. The condenser consisted of sections of eight consecutive double-pipe heat exchangers connected in series, with spacers in between for instrumentation. The sections were made of heat resistant Pyrex glass, with an inner tube (1.56-cm ID, 1.91-cm OD) and an outer tube (5.0-cm ID, 5.96-cm OD). The first six sections were 30.5 cm long and the last two sections were 60.6 cm and 217 cm long, respectively, giving a total condenser length, with spacers, of 486 cm.

Medium pressure steam (160 kPa, abs) from the McMaster Utility Plant was admitted via a pneumatic valve (V1), a steam orifice meter (0S), and a pulsing valve (V2), into the inlet plenum of the test section (BP). The steam condition just upstream of V1 was typically set at 60 bar and 170°C. The pressurized steam from the inlet plenum then rose through the inner tube of the vertical test column where part or all of it was condensed, and depending on the particular experimental conditions, the condensate flowed back in countercurrent fashion into the inlet plenum, or flowed upward with the vapor into the exit plenum (TP), which was open to the atmosphere. Any steam and condensate in the exit plenum were separated by gravity, and the wet steam leaving the plenum was condensed in a multi-tube heat exchanger and measured; the separated condensate was also collected and measured.

Cooling water was admitted via a mixing valve (V3) which was used to adjust its temperature, a cooling water orifice meter (OW) equipped with a U-tube water manometer, into the outer jacket of the test section. The exit cooling water from the test section was piped to the drain.

Altogether the sensors in the loop consisted of ten T-type thermocouples, ten Valdyne variable-reluctance pressure transducers, six capacitance-type void fraction meters, and a number of Borden gauges, as shown in Figure 1.

At a point just upstream of the steam orifice meter the steam pressure was measured with the pressure transducer P1 and the Borden gauge BG2, and its temperature was measured with thermocouple T1. The pressure drop across the orifice was measured with the differential pressure transducer P2. The frequency of the pulsing valve was measured with a timer-clock.

Inside the inlet plenum the temperature and pressure of the steam were measured with the thermocouple T3 and pressure transducer P4 respectively, while the temperature of the condensate was measured with the thermocouple T2 located at the bottom of the inlet plenum. A differential pressure transducer P3 measured the static pressure at the bottom of the condensate and was one of the means used to determine the amount of condensate in the inlet plenum. Another means used to determine the amount of condensate was with the aid of the level meter LM located outside of the inlet plenum. Additionally, the condensate in the inlet plenum was collected and weighed with a high-accuracy balance scale at the end of each experiment; this measurement was used to evaluate the time-averaged condensate reflux rates from the column.

The temperature of the condensate was measured all along the test section using thermocouples T5, T6, and T8. The temperature of any steam condensate mixture ejected to the exit plenum was measured with the thermocouple T9. Differential pressure transducers (P5, P6, P7, P8, and P9) were used to determine the pressure drops across designated sections of the primary side of the test column, as depicted in Figure 1. The pressure inside the exit plenum was measured with the pressure transducer P10.

The temperature of the cooling water (secondary side) was measured at the inlet (T4), at roughly mid-height (T7), and at the exit (T10). The pressure drop across the cooling water orifice was measured with the U-tube manometer (M) containing Marine-blue fluid.

Error estimates

The errors in the experimental results presented in the next section were comprised of systematic and random errors arising from instrument measurements, and from systematic and random deviations in the physical phenomenon being observed.

Notation

ΔP	Pressure drop, Pa or kPa
ΔT_{sub}	$T_{sat} - T_{sub}$ = degree of subcooling, °C
C_1	Constant in Wallis correlation
C_2	Constant in Kutateladze correlation
D	Tube diameter, m
f	Fraction of the admitted steam condensed at the inlet
g	Gravitational acceleration, m/s^2
j	Superficial velocity, m/s
J_k^*	Wallis parameter, defined in Equation 3
K_k	Kutateladze parameter, defined in Equation 4
L	Condensing region length, cm
$\dot{m}$	Mass flow rate, g/min
$\dot{m}_c$	Condensation rate, g/min
$\dot{m}_r$	Condensate reflux rate, g/min
P	Absolute pressure, Pa
Q	Heat flow, W
T	Temperature °C

Greek letters

ρ	Density, kg/m^3
σ	Surface tension, N/m

Subscripts

e	Effective
f	Condensate
g	Vapor
i	Phase i
o	Tube inlet
sat	Saturation
sub	Subcooling

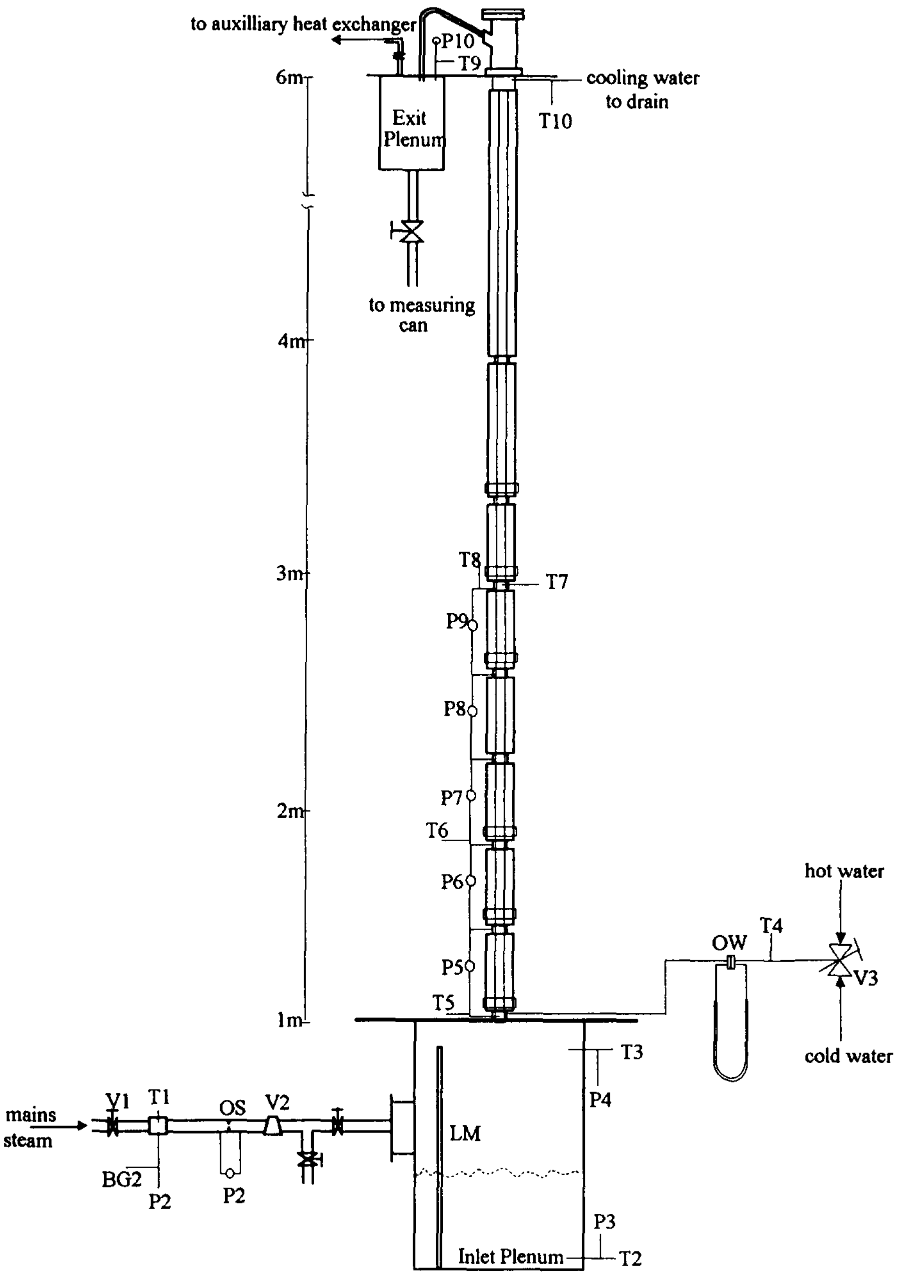

Figure 1 Test facility

The reflux condensation phenomenon itself was inherently unstable, and additional instability was artificially imposed on the process by the pulsations in the steam flow. Thus, as instability was an important part of the process itself, it is difficult to distinguish systematic and random deviations in set point from the true experimental results. Each experimental point was obtained by running the condenser for 3 h encompassing four equally spaced acquisition cycles. These separate groups of data were compared for consistency at the end of an experiment and then averaged to establish the experimental result.

The error in the pressure transducer readings, as given by the manufacturers, was ±0.5 percent full scale. The error in the calibration of pressure transducers was estimated at a maximum of ±0.1 mm Hg, or ±0.0133 kPa. The error in the voltage readings of the data logger, as specified by the manufacturers, was ±0.15 percent of current voltage value. For full scale demodulator settings of 10 V, the maximum error in the voltage readings of the pressure transducers was ±0.015 V. Altogether, the maximum error in the pressure transducer readings was ±0.9 kPa for P1 and P4, ±0.23 kPa for P3, and ±0.4 kPa for the rest. The accuracy of the thermocouple measurements, as specified by the manufacturers, was ±0.5°C. The basic accuracy of the data logger with electronic ice points, as specified by the manufacturers, was estimated at a maximum of ±1°C, to give a maximum total error in the thermocouple measurements of ±1.5°C. The maximum error in the steam orifice meter readings was ±5 percent. The maximum error in the condensate measurements, including human errors and the accuracy of the balance scale, was put at ±3 percent. The cooling water flow rates were actual measured values; the error in these measurements was less than ±1 percent.

In the experimental results presented in the following sections, the maximum error in the operating pressure and pressure drops was estimated at ±0.9 kPa, the maximum error in the measured mass flow rates was ±5 percent, the maximum errors in the reported average condensation rates and reflux rates were ±3 percent, and the maximum error in the stated heat removal rates was ±5 percent. The maximum error in the stated average condensing region lengths was estimated at ±5 cm because of the oscillation of the single phase region. Finally, the maximum error in the dimensionless steam and condensate flow rates presented subsequently was estimated at ±3 percent of all stated values. All errors were estimated at 95 percent confidence level.

Experimental results and discussion

Flow regime observations

Steady inlet steam flow. The flow regimes observed in the test section as a function of steam flow were as shown in Figure 2. These flow regimes were similar to those observed by Banerjee et al. (1983). At very low mass flow rates and system pressures a wavy condensate film was observed to flow downward countercurrent to the upward steam flow. All injected steam was condensed in a very short length of tube. The mass flow rate and system pressure, the condensation length, and readings from all sensors were constant, and conditions were truly steady. This mode of operation was referred to as reflux condensation without water column.

As the inlet mass flow rate was increased further in this mode, a marked entrainment of liquid droplets in the steam core was observed, signaling the onset of flooding in the condenser. At a certain inlet mass flow rate, a chaotic flow pattern resulted in the tube, with most of the condensate carried up with the steam. This transition to churn-annular concurrent flow in the tube may have corresponded to the onset of flooding at the tube inlet. The upward condensate flow bridged the tube above the two-phase condensing region to establish an oscillating single-phase condensate (water) column.

Although the water column oscillated at low frequency, its behavior was essentially static in the mean, and it was presumed to be sustained by a balance of its weight and the back pressure it exerted on the condensing region upstream, which increased steadily with the length of the column. The compression-piston effect of these slow oscillations on the two-phase region led to further instantaneous jumps in the operating pressure, superimposed on this steady increase, and the column was finally ejected when the total instantaneous system pressure upstream was high enough to overcome the gravitational weight of the water column and give it a sufficient initial momentum upward to the exit plenum. Following this carry-over, the back pressure exerted on the system was removed, and the operating pressure dramatically decreased accordingly. Thereafter the single-phase liquid region was quickly reestablished and the cycle repeated again. The cycle period was usually long, typically more than 5 min. Because of the nature of this cyclic operation, this mode of operation was categorized as cyclic carry-over mode with a quasi-static water column, and is subsequently referred to as the first carry-over mode of operation for convenience.

As the inlet mass flow rate was increased beyond the first carry-over mode, the system underwent transition to the second carry-over mode. The flow regime observed was essentially the same as was observed in the first carry-over mode, but the water column was oscillating at a much faster frequency, and as opposed to quasi-static nature of the column in the first carry-over mode, its behavior was fully dynamic. This pointed to an unstable operation governed by instability, rather than by gravity, and signaled a transition state before the onset of steady two-phase climbing film flow in the tube. Unlike in the first carry-over mode, the system underwent two-phase

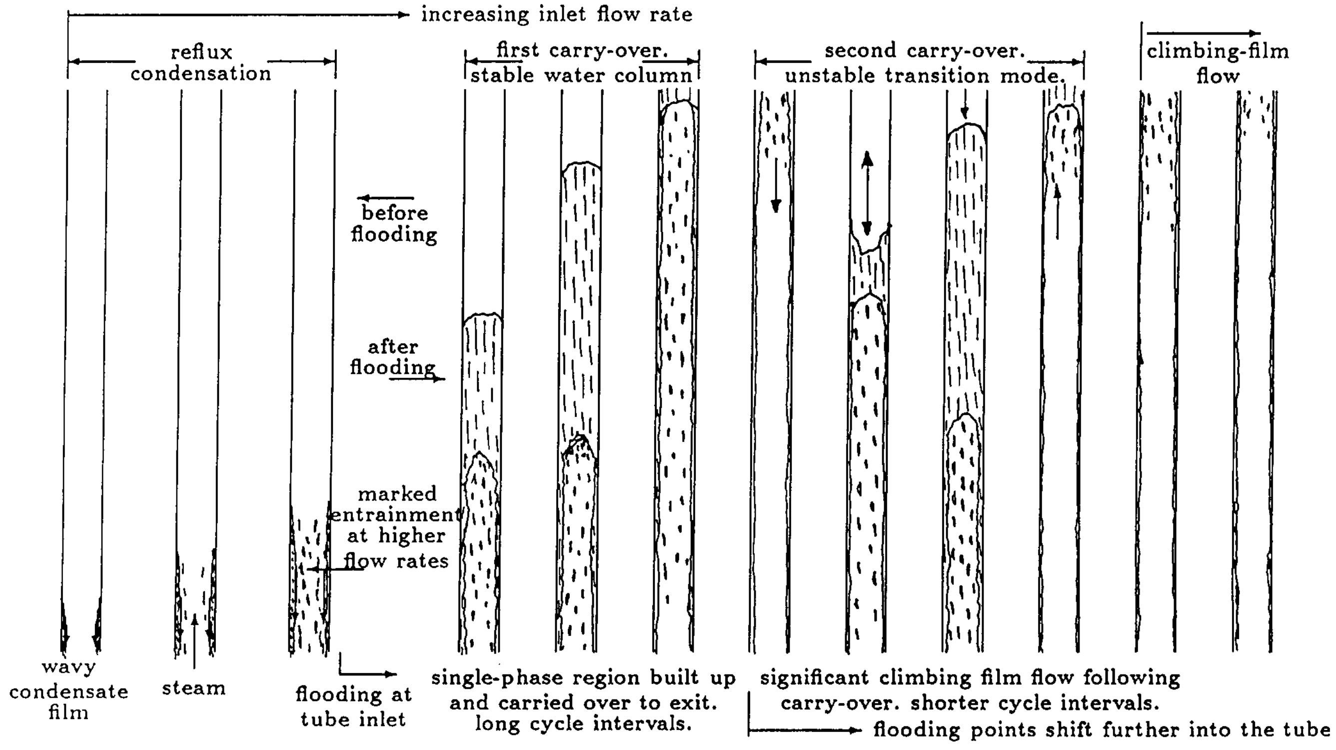

Figure 2 Schematics of the flow regimes observed under steady inlet flow

climbing film flow for a while immediately following carry-over, while the operating pressure decreased. As the system pressure dropped to the initial value just before the formation of the water column, the climbing film flow regime could not be sustained any further, and the system thus reverted back to reflux condensation; thereafter, the condensate column was immediately reestablished and the cycle repeated again. The cycle period was shorter and less regular than in the first carry-over mode, being generally less than 60 s. Because of the nature of the carry-over operation, this operating mode was categorized as carry-over mode with a dynamic water column, or the second carry-over mode. In both carry-over modes, the flow pattern in the two-phase condensing region was churn annular flow.

As the inlet steam flow rate was increased beyond the second carry-over mode, steady two-phase climbing film flow was established in the condenser. There was no condensate reflux from the test section to the inlet plenum in this mode, except for a small fraction condensed around the tube inlet and the exit of the inlet plenum. The climbing film flow mode was not investigated in this study, and except for reference, it is not discussed in this report.

Pulsed inlet steam flow. The primary effect of pulsing the steam flow was to disperse or prevent the formation of a stable and growing liquid column above the two-phase condensing region. However the extent to which this effect was manifested depended primarily on the frequency of pulsation of the inlet mass flow. Under a low constant pulsing frequency (0.14 Hz) the phenomenon observed in the test section, as the (average) inlet mass flow rate was steadily increased, could be described as follows.

In the low inlet mass flow rate range, corresponding to lower amplitude pulsations in the inlet mass flow rate and operating pressure than those shown in Figure 3, the phenomenon observed in the test section was intermittent film condensation of steam, but unlike in the steady inlet mass flow case the maximum condensation length that could be attained without establishing a water column was considerably higher. This was because steam flow rate increased and decreased in each pulse cycle, and there was not enough time for upward condensate flow to bridge the tube and establish a water column. This destabilizing effect thus afforded much higher inlet flow rates to be used in the condenser without establishing the single-phase region. Like in the steady inlet flow case this mode of operation was categorized as reflux condensation without water column and is shown in Figure 4.

As the inlet mass flow rate was increased, corresponding to relatively higher-amplitude pulsations in the inlet steam flow and operating pressure (Figure 3), a plug of condensate formed

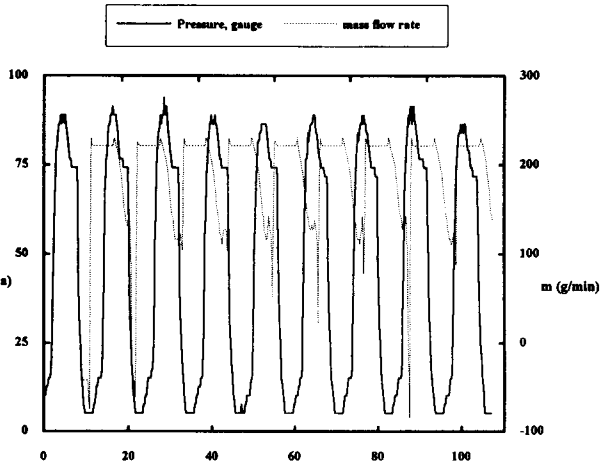

Figure 3 Typical pulsed-flow system pressure and mass flow rate transient in a dispersed water

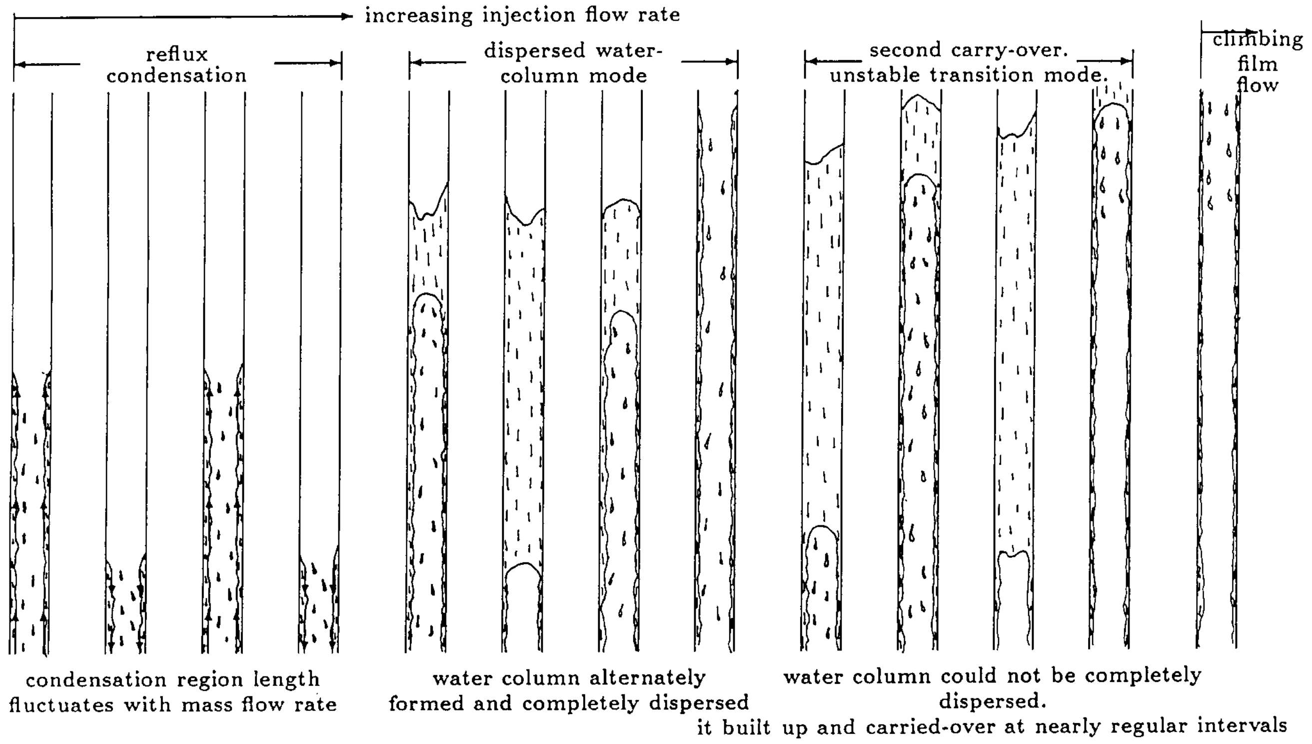

Figure 4 Schematics of the flow regimes observed at 0.14-Hz pulse frequency

above the refluxing condensate as the steam flow rate and system pressure decreased in each cycle (Figure 4). Unlike the manner of establishing the water column as observed in steady inlet flow case, which was due to flooding in the tube, the formation of a water column in the pulsed inlet flow experiments was clearly due to condensate film downflow bridging the tube and coalescing into a water column that flowed down under its own weight. This coalescence meant that the water column increased in length as the steam flow rate decreased, and it was longest at the minimum steam flow rate, which may be zero for pulsing at the lower range of average inlet steam flow rates. Some of the water column got dumped to the inlet plenum at low average inlet flow rates, but mostly the water column was churned and accelerated upward as the steam flow rate increased in the next pulse cycle. This churning and mixing motion with the expanding steam resulted in the depletion of single-phase region, and at some point before the end of the expansion, the water column became completely dispersed in the steam. Thus the water column formation was intermittent, and all the injected steam was condensed and refluxed back to the inlet plenum. This mode of operation was categorized as reflux condensation with intermittent water column or simply the dispersed water column mode. It was obtained only for the lower frequency 0.08 Hz and 0.14 Hz pulsed inlet flow experiments, and was not obtained for the 0.25 Hz pulsed inlet flow experiments. The maximum length of the water column observed in this mode was about 150 cm.

As the inlet steam flow rate was increased beyond the dispersed water column mode, corresponding to still higher-amplitude pulsations in the inlet mass flow rate and operating pressure those of the earlier modes of operation (Figure 3), the water column formed as the steam flow rate decreased in each pulse was too long (Figure 4, typically greater than 200 cm), and thus it could not be completely dispersed by the expanding steam in the subsequent pulse cycle. Instead the length of the column was shortened appreciably as the inlet steam flow rate increased, and as the latter decreased, the column lengthened to a larger maximum value than in the preceding pulse cycle. Thus, on the average, the water column built up and was dumped to the exit plenum at nearly regular intervals. Because the admission flow rates in this mode were relatively high, the carry-over operation was one governed by instability, as witnessed by the short almost regular (as opposed to the long regular) cycle intervals. Thus this mode of operation was the second carry-over mode as observed for steady inlet flow experiments. All carry-over operations in the pulsed inlet flow experiments investigated in this study were in this mode.

When the steam inlet steam flow rate was increased beyond the carry-over mode, two-phase climbing film flow was established in the tube.

The four modes described previously were also observed for the lower-frequency 0.08-Hz pulsed inlet flow experiments, but the carry-over operation occurred at roughly each pulse cycle.

For the higher-frequency 0.25-Hz pulsed inlet flow experiments, the system underwent transition directly from the reflux condensation without water column mode to the second carry-over mode; the dispersed column mode was not observed.

Data analysis and discussion

Steam inlet flow rates and operating pressure. The time-averaged system pressure as a function of time-averaged inlet steam mass flow rate is shown in Figure 5. Note that this characteristic curve was similar to the results obtained by Chang et al. (1985) in 4- and 11-tube banks, and by Calia and Griffith (1982) in a 4-tube bank.

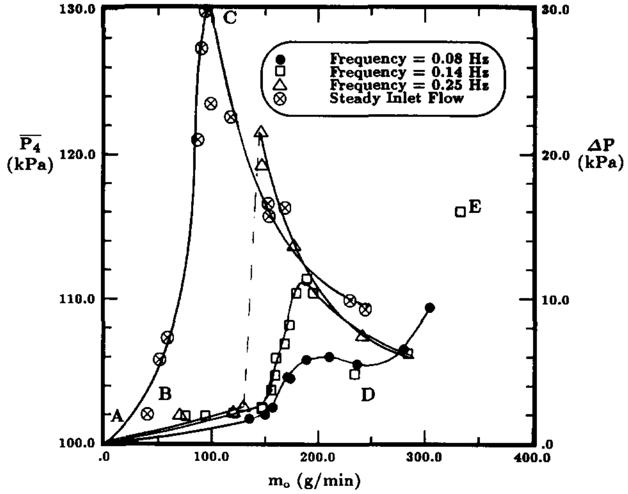

Figure 5 Time-averaged absolute system pressure P_4 and pressure drop ΔP *vs* average inlet mass flow rate $\bar{m}_0$

In steady inlet steam flow experiments, as well as in pulsed inlet flow experiments, the region A–B in Figure 5 corresponded to the first mode of operation in which complete condensation of steam occurred without the formation of water column. Because there was no water column above the condensing region, there was no back pressure effect from the former, and hence the pressure drop was all frictional. As indicated by Figure 5, the maximum mass flow rates attained in this mode were greater with flow pulsation. This improvement in the throughput of the condenser depended on the frequency of pulsation; although the average pressure drop across the condenser decreased as the frequency of pulsation was decreased, the maximum time-averaged mass flow rate in the condenser, in reflux condensation mode, was achieved at 0.14-Hz pulse frequency.

For steady inlet flow experiments point B in Figure 5 corresponded to the minimum mass flow rate at which the net upward condensate flow bridged the tube to establish a single-phase region (i.e., the flooding point). Thus there was a sharp increase in the system pressure due to the plugging effect of the water column. The region B–C corresponded to the gravity-governed carry-over mode with a quasi-static water column, during which an incremental increase in the admission rate resulted in a huge increase in the operating pressure, as may be observed from Figure 5. As stated earlier in the last section, this mode of operation was not observed in the pulsed inlet flow experiments conducted in the study. For pulsed inlet flow experiments the region B–C corresponded to the dispersed water column mode. The intermittent formation of the water column resulted in slight increases in the operating pressure, but because the water column was alternately dispersed, the operating pressure—and pressure drop—were much smaller than in the carry-over modes. The dispersed column mode was not observed for 0.25-Hz pulsed inlet flow experiments, as indicated by the dashed lines in Figure 5. The maximum mass flow rate attained in this mode was slightly higher for the 0.14-Hz pulsing frequency than for the 0.08-Hz pulsing frequency, while the maximum operating pressure obtained in the later was lower.

The point C in Figure 5 was the transition point to the instability-governed carry-over mode with unstable water column, for steady inlet flow experiments. The region C–D corresponded to the second carry-over mode and showed the opposite trend to the observations made in the first carry-over mode: slight increases in the steam admission rates resulted in large drops in the operating pressure. This was because the instability increased as the mass flow rate increased, as was evidenced by the much higher and less regular oscillating frequency of the single-phase region observed as the mass flow rate was increased. The associated shorter cycle intervals (more frequent carry-over) thus resulted in smaller levels of operating pressure and pressure drop across the tube. All carry-over operations in pulsed inlet flow experiments were in this mode.

The maximum inlet steam flow rates achieved in this mode, without a significant amount of climbing film flow being associated with the carry-over operation, were approximately the same for all experiments. This suggested that the condenser would undergo transition to full climbing-film flow mode at the same average inlet mass flow rate and operating pressure for all experiments, which was a reasonable conjecture because this operating limit would be governed by factors external to the nature of the steam flow, in particular the cooling water inlet flow and temperature (wall heat flux), the size and length of the tube (heat-transfer area), and the film coefficient on the tube wall.

Thus the real effect of the low-frequency steam pulsations was to eliminate the stable carry-over mode entirely and to push the onset of the unstable carry-over mode to higher vapor flow rates. This was equivalent to expanding the operating range of the condenser while still maintaining total product extraction, under reflux condensation and dispersed water column modes of operation.

The region D–E was climbing-film operation for all experiments. As mentioned earlier, there was no reflux to the inlet plenum in these experiments, except for the small fraction condensed around the tube inlet. As such this mode of operation did not concern the present study.

Heat removal capability. The time-averaged heat removal rates obtained for the various experiments were plotted as shown in Figure 6. The corresponding condensation rates, calculated by assuming no subcooling, are also shown on the figure. This figure shows that remarkable improvements in the heat removal capability of the condenser were achieved by steam pulsation, which was directly associated to the higher admission flow rates attained with pulsation.

The improved heat removal capability with pulsation may be attributed to three factors: the longer condensing lengths attained as the expanding steam pushed the column of condensate toward the exit, as shown in Figure 7 the direct contact heat transfer arising from the violent mixing of steam and subcooled condensate, and to a lesser extent the improved heat transfer coefficients arising from the higher levels of turbulence in the liquid film adjacent to the tube wall. This later factor may become important in the condensation of hydrocarbons. For a given time-averaged operating pressure and pressure drop, Figure 6 shows that, in terms of the time-averaged heat removal rate, the best performance was obtained at 0.08-Hz frequency, among the three frequencies investigated in this study.

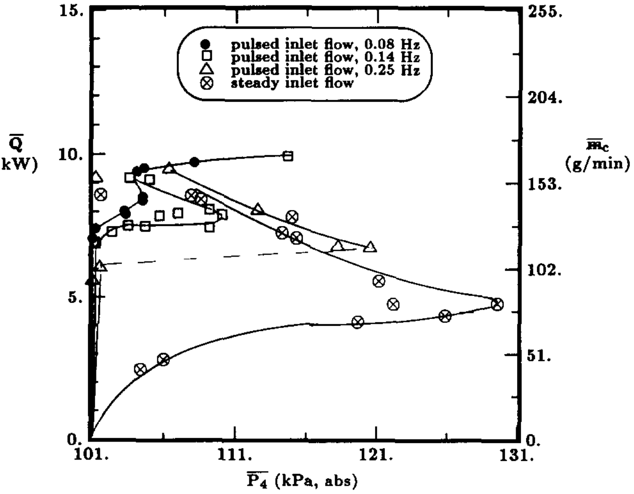

Figure 6 Time-averaged heat removal $\bar{Q}$ and time-averaged condensation rate $\bar{\dot{m}}_c$ rate *vs* system pressure $\bar{P}_4$

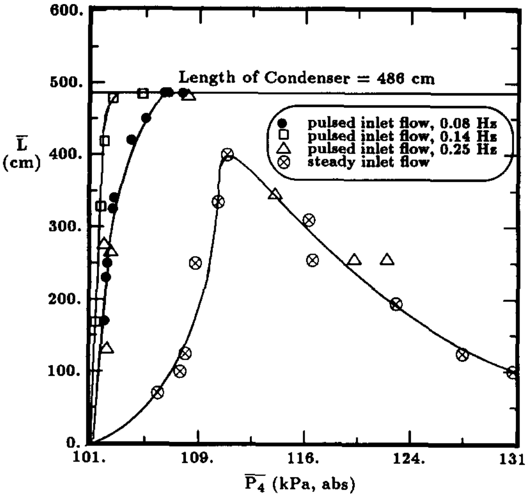

Figure 7 Time-averaged condensation length $\bar{L}$ *vs* system pressure $\bar{P}_4$

Beyond the second carry-over mode the heat removal rate tended to saturate, as shown in Figure 6. This saturation corresponded to the maximum heat removal rate that could be attained in steady-state climbing-film flow.

Flooding models for the reflux condenser

As was noted in the last section and elsewhere in the literature (Butterword 1973; Calia and Griffith 1982; Chang et al. 1985; Chang and Girard 1983) the formation of single-phase region, which constituted the upper limit of the reflux condensation process, was due to flooding in the tube. Flooding is a term used to describe the limiting point of countercurrent gas-liquid flow at which there is considerable flow instability due to the formation of standing waves on the liquid surface, resulting in a chaotic flow pattern with most of the liquid entrained in the gas core. In the reflux condenser, this liquid entrainment led to most of the condensate being carried up with the steam and bridging the tube above the condensing region to build a single-phase water column. To examine the limiting phenomenon of condensate column formation in the partial condenser more closely, the basic ideas presented by Tien (1977) are modified to derive a simple model based on flooding.

Most analytical and empirical flooding models are stated in either of two forms

$$J_g^{*1/2} + J_f^{*1/2} = C_1 \qquad (1)$$

or

$$K_g^{1/2} + K_f^{1/2} = C_2 \qquad (2)$$

where J_k^* and K_k are the Wallis (1969) and Kutateladze (1972) parameters, defined respectively as

$$J_k^* = \frac{\rho_k^{1/2} j_k}{[gD(\rho_f - \rho_g)]^{1/2}} \tag{3}$$

$$K_k = \frac{\rho_k^{1/2} j_k}{[g\sigma(\rho_f - \rho_g)]^{1/4}} \tag{4}$$

In general, the Wallis-type correlation (Equation 1) is more valid for small tube diameters while the Kutateladze-type correlation (Equation 2) is valid for large tube diameters. The usual criterion is the dimensionless tube diameter, or the so-called Bond number,

$$D^* = D\left[\frac{g(\rho_f - \rho_g)}{\sigma}\right]^{1/2} \tag{5}$$

For the reflux condenser, evaluating properties at saturation, $D^* = 6$. However, the model derived using the Kutateladze parameter compared better with the present experimental data. By considering the limiting case of zero penetration ($J_f^* \rightarrow 0$), Kutateladze (1972) had analytically determined the constant $C_2 = \sqrt{3.2}$.

In formulating an analytical model for flooding it was assumed, as stated in the preceding section, that the first carry-over mode of operation was as result of flooding at the entrance of the tube. As suggested by Tien (1977), vapor condensation at the tube inlet due to its interaction with the subcooled condensate would reduce the effective vapor entry flux. Thus

$$\dot{m}_{ge} = \dot{m}_{go} - f\dot{m}_{go} = (1 - f)\dot{m}_{go} \tag{6}$$

Similarly the effective vapor superficial velocity is

$$j_{ge} = (1 - f)j_{go} \tag{7}$$

The assumption of a localized flooding at the tube entrance afforded a local heat balance between the condensate and the steam at this location in order to determine the fraction f, as shown in Figure 8. In doing this we assumed that the heat of condensation was used to bring the condensate from the subcooled state to saturation (Tien 1977). Thus from Figure 8,

$$c_p \Delta T_{sub}(\dot{m}_{fo} - f\dot{m}_{go}) = f\dot{m}_{go}h_{fg}$$

from which we obtain

$$f = \left[\frac{c_p \Delta T_{sub}}{h_{fg} + c_p \Delta T_{sub}}\right]\left(\frac{\rho_f}{\rho_g}\right)\left(\frac{j_{fo}}{j_{go}}\right)$$

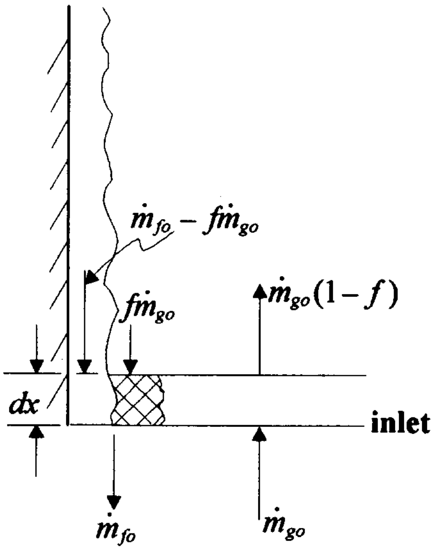

Figure 8 Flooding at tube entrance

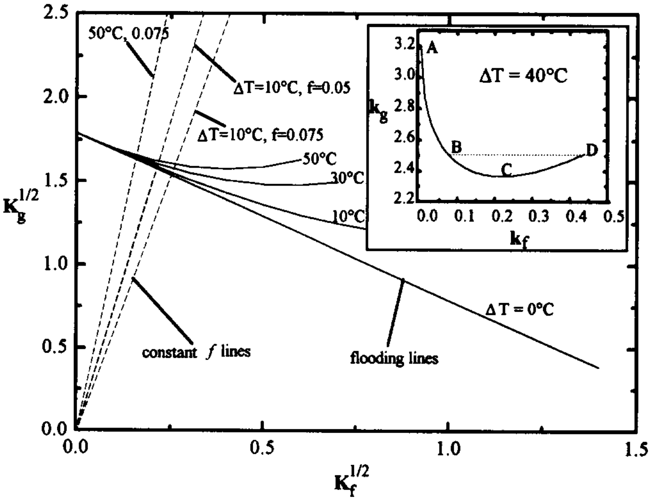

Figure 9 Values of *f* and theoretical flooding lines for various levels of subcooling. *Inset*: Flooding in the $K_f - K_g$ plane for 40°C subcooling

The superficial velocities may be expressed in terms of the Kutateladze parameter (Equation 4); thus f is given in terms of these parameters as

$$f = \left[\frac{c_p \Delta T_{sub}}{h_{fg} + c_p \Delta T_{sub}}\right]\left(\frac{\rho_f}{\rho_g}\right)^{1/2}\left(\frac{K_{fo}}{K_{go}}\right) \tag{8}$$

Thus employing the effective superficial vapor flux in the Kutateladze variable, the theoretical flooding model may be derived

$$(1 - f)^{1/2}K_{go}^{1/2} + K_{fo}^{1/2} = C_2 \tag{9}$$

where $C_2 = \sqrt{3.2}$ (Kutateladze 1972).

Evaluating properties at saturation, Equation 9 was plotted for various levels of subcooling, as shown in Figure 9. The typical values of subcooling measured at the tube entrance ranged from 10°C–45°C; the corresponding range of fractions of steam condensed at the tube inlet is also shown in Figure 9. The results showed that above a level of subcooling of approximately 20°C, flooding in the reflux condenser would exhibit a hysteresis effect due to the existence of minima in the flooding lines. This may be seen by examining the flooding line in the $K_f - K_g$ plane shown in the inset for 40°C subcooling. Suppose the vapor flow was progressively reduced from point D along the flooding curve; the condensate reflux rate would reduce correspondingly until point C was reached. Below A–C the model predicted the existence of bistable modes of operation at a given inlet steam flow rate, because it would be possible for the operation point to exist on the path A–B as well as on the path C–B. Thus if the inlet steam flow rate was reduced to point C, the operation point may suddenly jump to point A, where the condensate reflux rate is zero or relatively very small. On further reduction of the vapor flow rate below A–C the operation of the system would be unsteady and erratic because the operating points would not be unique, because the system could operate on the path A–B as well as on the path B–C. This hysteresis effect was observed in the reflux condenser at steady inlet steam flow. Once the liquid column was established the system alternated in an irregular manner between times when the length of the water column was observed to grow fast and other times when the growth was very slow. This unsteady operation would correspond to a jump in operation point between the paths A–B and B–C. If the steam flow rate was reduced below a certain level, which would correspond to the points where the flooding lines intersect the ideal reflux line, as at point B in Figure 9, the water column may collapse and the system may revert back to steady operation in the reflux condensation mode, otherwise the water column would be ejected to the exit plenum. Further, as may be observed from Figure 9, the degree of hysteresis decreased as the degree of subcooling was increased and may well disappear at higher levels of subcooling. This is consistent with the observations of Liu et al. (1980), who observed no hysteresis at higher degrees subcooling ($\Delta T = 75°C$) during the decrease of steam flow on the heat transfer flooding with steam and water in a 0.15-m diameter vertical pipe.

The flooding model of Equation 9 was compared with experimental data in Figure 10. As may be noted, it was in excellent agreement with the experimental results of steady inlet flow first carry-over operation within a level of subcooling of between 10°C and 30°C, which were within the range of condensate subcooling measured during the experiments (Obinelo 1990).

It may be observed that the model was not able to predict the second carry-over data for all experiments, because in this mode of operation flooding was not at the tube inlet but further inward in the tube. This would invalidate the localized heat balance made in deriving the fraction f (Equation 8). Furthermore the flooding point was not localized at a specific location along the tube, but shifted up and down because of the instability of the phenomenon, and this variation also depended on the mass flow rate. Thus a single value of f could not be defined for all experiments in this mode, and in light of the above, even for the same experiment in this mode.

Another factor that may have contributed to the discrepancy between the pulsed inlet flow experimental results and the theoretical models involved the interaction of the expanding steam and the single-phase condensate column. This interaction may be seen as an additional liquid momentum whose effect would be to raise the vapor flooding velocity. In terms of the present model the influence of this additional downward momentum would be to raise the Kutateladze hydrodynamic constant C_2. The dashed line shown in Figure 10 was obtained by employing $C_2 = 2.2$ in Equation 9. As may be observed the model correlated the carry-over mode results quite well.

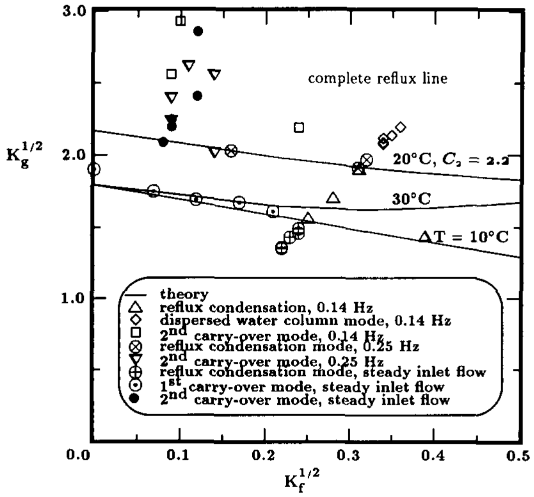

Figure 10 Comparison of theoretical flooding model (Equation 9) with present experiment

Practical significance

As was pointed out in the introductory section, the main disadvantage of using reflux condensers in chemical distillation processes, among others (Butterword 1973), is the capacity limitation resulting from flooding. The main objective of this study was to eliminate or destabilize the limiting water column formed as a result of flooding in the condenser, and thereby expand the capacity and heat removal rates in the condenser. As indicated by the results presented, this objective was largely achieved.

A closely associated and important objective of the study was possible means of heat-transfer augmentation by application of controlled pulsations to a working fluid. These controlled pulsations are potentially able to increase the local heat transfer coefficients on the heat transfer surfaces by inducing higher levels of turbulence in the thermal boundary layer, as has indeed been shown by the results presented hitherto. In certain applications, this may be a more attractive means of heat-transfer augmentation than the additional cost of using fins or special surfaces.

One major problem in condenser applications in general is the venting of noncondensible gases, which, among other things, raises the operating pressure and reduces the effectiveness of heat transfer by occupying a major portion of the heat transfer surface, especially at low pressures. The nature of vapor-condensate interaction when the vapor flow is pulsed, as exemplified by steam-condensate interaction in this study, may aid the venting of noncondensibles in the case of components containing large amounts of noncondensibles.

Conclusion

A study of the effects of steam pulsation on the reflux condensation phenomenon was carried out. The results of the experimental study are summarized in the following.

When the inlet steam flow was increased at certain flow rates, the steam flow in the condenser was limited by flooding at the tube entrance, which resulted in the formation of a stable water column above the condensing region. The growth and subsequent carry-over of this water column to the exit plenum resulted in a cyclic operation with wide variations in the operating pressure and large pressure drops across the condenser, and resulted in a relatively low steam flow rate that could be used in the condenser in reflux condensation. The application of controlled pulsations to the inlet steam flow was found to destabilize the water column and led to a several-fold increase in the condensation capacity and heat removal rates in the condenser.

The increase in condensation capacity and heat removal rate was found to be dependent on the frequency of steam pulsation; the experimental results suggest that an optimum frequency exists at which the condensation capacity and heat removal capability of the reflux condenser would be a maximum. The time-averaged pressure drops across the tube, conversely, were found to decrease as the frequency of pulsation was decreased.

A theoretical model based on flooding was derived for the phenomenon and compared with the experimental results. The model was in agreement with the first carry-over mode experimental results and revealed that the formation of water column in steady inlet flow experiments was due to flooding at the tube entrance.

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