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GRAVITY EFFECT ON THE DISTRIBUTION OF REFRIGERANT FLOW IN A MULTI-CIRCUITED CONDENSER

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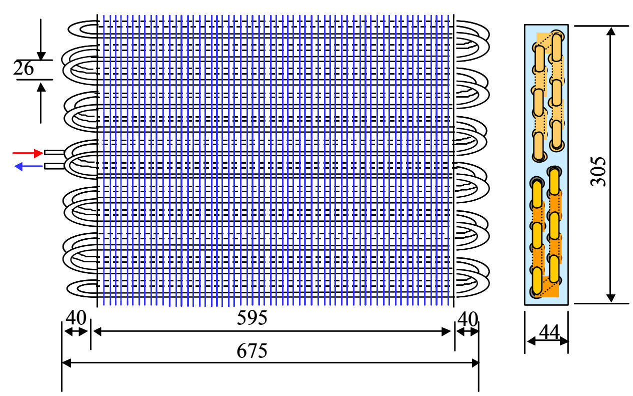
ABSTRACT

Gravity in the multi-circuited condenser affects the refrigerant flow rate distribution owing to the gravitational pressure drop that occurs mainly in the U-bend tubes in fin and tube condensers having horizontal tubes. This effect is studied using experimental and numerical approaches. A condenser having two 'nU' type circuits is selected, and the temperature variation of the refrigerant side is calculated, and then compared with test data along each circuit. The gravity-affected region is shown in the table with rows of air velocities and columns of refrigerant flow rates. The region is well matched each other between experiment and our newly designed calculation.

INTRODUCTION

The distribution of the refrigerant flow rate in a multi-circuited condenser is a function of the relative magnitude of the pressure drop in each flow circuit, not the absolute magnitude of the pressure drop. Once different pressure drops occur in each multi-circuited circuit on the refrigerant side, the refrigerant flow rate in each circuit will change to produce a uniform pressure drop distribution for common inputs and outputs.

Wang et al. (1999) experimentally studied the effect of the circuit arrangement on the performance of air-cooled condensers. They tested eight circuits, of which one showed the gravity effect. The 'nU' type condenser like Fig. 1 had a large temperature deviation between the upper 'n' and lower 'U' type circuits at mass fluxes below 200 kg/m^{2}s. They guessed that the gravitational pressure drop in the up portion of the upper circuit was 4-5% of the total pressure drop, because the higher void fraction of the high quality regions decreased the gravitational pressure drop. However, the effect of gravity was reversed in the down portion of the upper circuit, and the quantity of liquid condensate was much larger than that in the up portion of the upper circuit. Hence, the pressure gain in the upper circuit was very pronounced, and was approximately 30-40% of the total pressure drop. Conversely to the pressure gain in the upper circuit, the gravitational gradient of the lower circuit can be regarded as a pressure loss. Therefore, the upper circuit would require a higher mass flow rate to give the same pressure drop between the upper and lower circuits. However, they tested only at a fixed air velocity of 1 m/s, and did not examine the gravity effect in much detail.



- unit: mm
- wavy fin and smooth tube
- front area: 595 mm x 305 mm
- row pitch: 22 mm
- step pitch: 26.0 mm
- fin pitch: 2.0 mm
- out diameter: 9.52 mm
- tube thickness: 0.36 mm
- expansion ratio: 1.076

Fig. 1 Test zones of previous and present studies

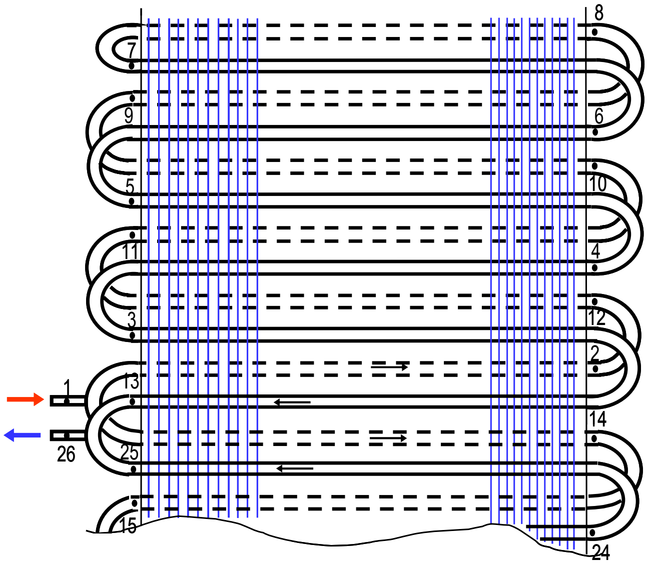


Fig. 2 Temperature measuring points of the upper ‘n’-type circuit

As the air velocity increases, the compensation for the pressure drop due to momentum recovery also increases, as does the sub-cooled portion in each flow circuit shown in Fig. 1. In the condenser, the liquid refrigerant in each flow circuit will flow in the opposite direction after the sub-cooled point. In this case, the effect of the gravitational pressure drop may become dominant if the friction term is small enough owing to the low refrigerant flow rate and the pressure recovery from the refrigerant condensation.

In this study, numerical calculations are performed and compared with test data (Lee and Kim, 2004) for combinations of different air velocities and refrigerant flow rates. The gravity-affected region will be shown in a table with rows of air flow rates and columns of refrigerant flow rates, and the critical air velocity and refrigerant flow rate, which indicate the initiation of the gravity effect, be observed in the both of the test and calculation.

CALCULATION AND MEASUREMENT

Test Sample and Experiment

The specifications of the test sample are shown in Fig. 1. T-type thermocouples were attached to the surface of the extra tube wall out of end plate. Temperature measuring points of the upper ‘n’ type circuit are shown in Fig. 2, and other measuring points of the lower ‘U’ type circuit are similar in the opposite direction.

The tube wall temperatures will indicate the refrigerant temperature with negligible deviation because there is no airflow across the temperature measuring points and double-layered insulation covered the tube (heat transfer resistance of outside will be almost infinite). Those wall temperatures are used to find the sub-cooled point in the refrigerant flow path.

In the experiment (Lee and Kim, 2004), all of the data were collected to the computer by digital communication with the measurement modules. Three measurement modules were used in this test: a Yokogawa DA-100 and DR-240, and a Druck DPI-145. All of the thermocouples were calibrated to ±0.3°C over the range of 5-30°C with a precision thermometer (DP251, Omega). The accuracy of the pressure readings (DPI-145, Druck) was ±0.025%. The Pt 100Ω RTD sensors were calibrated to an accuracy of ±0.07°C with a precision thermometer (DP251, Omega). The tube wall temperatures were measured with T-type thermocouples, and the other temperatures were measured with the Pt 100Ω RTD sensors. Detail accuracies of the measurements and test facilities like the temperature controlled room, the nozzle flow meter system, and the refrigerant supply loop will be available in the paper of Lee and Kim (2004). And test data also will be available in the paper.

Data Reductions

To observe gravity effect in the test and calculation, temperatures are observed along refrigerant flow path. The gravity effect will be considered as negligible when the temperatures are same in each path of the upper ‘n’ type circuit and lower ‘U’ type circuit. Temperature detection points are like Fig. 2 in the test and calculation. The location will be expressed like the following equation

$$L_r = \frac{L_i - L_1}{L_{26} - L_1} \quad (1)$$

i= 2~13, the upper ‘n’ type circuit
14~25, the lower ‘U’ type circuit

where L_r will be 0 at the common inlet of 1, and 1 at the common outlet of 26. The temperature at the point of 26 may have big difference with data at 13 and 25, even though they have almost similar value of L_r. Mass averaged temperature of the points of 13 and 25 will be appear at the point of 26.

Numerical Calculations

Numerical simulation is based on the approach of Lee et al. (2002). They used section-by-section scheme to analysis the heat transfer rate along refrigerant flow path. Only several points are added or changed compared to their works: gravitational pressure drop in U-bend tube, different correlations for the heat transfer coefficient, and pressure drop to consider the effect of gravity dominant flow pattern inside the tube. Correlations are summaried in Table 1.

Table 1 Summary of correlations

Part	Category	Correlation
Heat transfer coefficient	wavy fin, air side	Modified Gray and Webb (1986)
	single phase, refrigerant side	Dittus-Boelter (see, Incropera, 1986)
	two phase, refrigerant side	Dobson and Chato (1998)
In-tube pressure drop	single phase, horizontal tube	Petukhov (1970)
	two phase, horizontal tube	Gronnerud (1979) Muller-Steinhagen (1986)
	single phase, U-bend tube	Ito (1960)

The gravitational pressure drop occurs in the U-bend tube of a fin and tube condenser. It can be calculated like the following Eq. (2):

$$\Delta P_g = \left(1-\alpha\right)\rho_l gH + \alpha\rho_v gH \qquad (2)$$

$$\Delta P_b = \frac{xv_v G}{2}\left(0.03\frac{L}{H}+0.9\right)+\lambda\Delta P_g \qquad (3)$$

Including the gravity term of Eq. (2), total pressure drop in U-bend tube can be calculated with Eq. (3). In this equation, the first term is Pierre (1964) correlation. The directional flag, λ, in the second term in Eq. (3) will be positive for the up flow, and negative for the down flow. The positive sign means pressure loss and the negative means pressure gain.

RESULTS AND DISCUSSION

Observation of the Gravity Effect

The gravity-affected region is determined from the deviation of the temperature profiles between the upper and lower circuits. For example, temperatures in Fig. 3(a) show that the gravity effect will be negligible. The temperatures between the upper and lower circuit are exactly same. Except the direction of refrigerant flow, the two circuits have the same inlet conditions: air velocity, temperature, refrigerant flow rate, condensing temperature, and inlet quality. Therefore, it can't be thought that the temperatures are reflected by any directional effect (or gravity effect) of refrigerant flow. But temperatures from test in Fig. 3(b) and Fig. 3(c) show that the gravity effect should be in the circuit. In this case, the temperature profiles between the upper and lower circuit become to have clear discrepancy. The difference of gravitational pressure drop, which can be expressed like Eq. (4), makes different flow of refrigerant in each flow circuit. Therefore start point of sub-cooling becomes different between the upper and lower circuit.

Simulation results for the gravity effect are also shown in Fig. 3(b) and Fig. 3(c). In Fig. 3(b), it is shown the numerical results can simulate the discrepancy of temperature between two circuits. In this calculation the second term in Eq. (5) is considered when the pressure drop in U-bend is calculated. However, the numerical results can't simulate the temperature discrepancy between two circuits as shown in Fig. 3(c) when the second term is not considered in the calculation.

Pressure Drops

The pressure drop in each circuit should be same because they have the common inlet and outlet. However, the refrigerant flow can be different to have same pressure drop in each flow circuit.

Pressure drops in condensers with horizontal tubes can be classified into four categories: frictional and momentum pressure drops in the horizontal tubes, and frictional and gravitational pressure drops in the U-bend tubes. The momentum pressure drop is mainly a function of the heat flux, and has the opposite sign to the friction term in the condenser; the momentum is recovered during the condensation process when the density changes from gas to liquid.

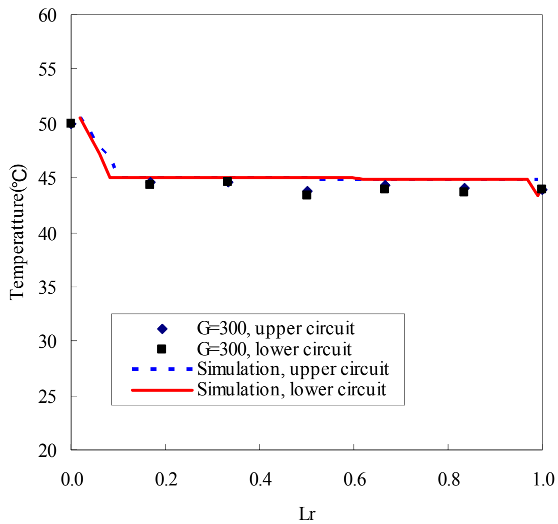
Fig. 4 shows those pressure drops obtained from numerical calculations. At the mass flux of 300 $kg/m^2.s$, those pressure drops are similar between the upper and lower circuit as shown in Fig. 4(a) and Fig. 4(b). But at the mass flux of 200 $kg/m^2.s$, those pressure drops are different, and the gravity term (sixth bar) has opposite sign as shown in Fig. 4(a) and Fig. 4(b)

Gravity Affected Region

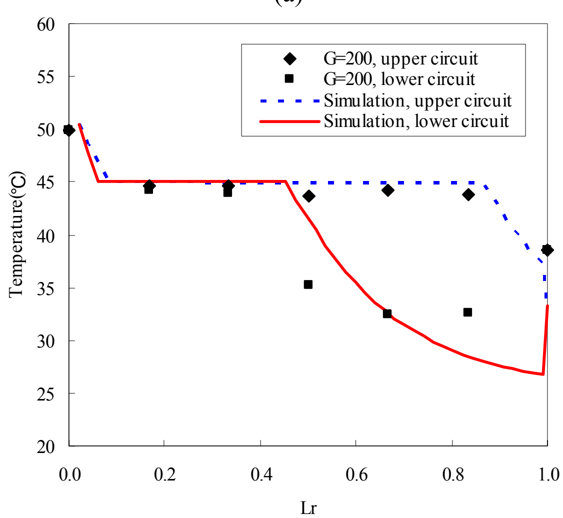
Table 2 shows the gravity-affected regions using the test and simulation data. The rows indicate the air velocities and the columns indicate the refrigerant flow rates. The 'o' and 'x' marks in the table indicate gravity-affected points and normal points from the numerical results, respectively; gravity effects were observed at the 'o' points but not the 'x' points. The gravity-affected region from test is shown as a shaded area in the table; raw data can be available in the paper of Lee and Kim (2004). It is shown that the numerical results well simulate gravity affected region even though there is a little gap between test and numerical results.

The gravity effect becomes greater as the refrigerant flow rate decreases and the air velocity increases. At a given air velocity, there is a critical refrigerant flow rate at which the gravity effect is first apparent; this is the first point of the shaded region from right in each row of Table 2. As the refrigerant flow rate decreases below the critical flow rate, the gravity effect develops further, producing greater temperature deviations between the two circuits.

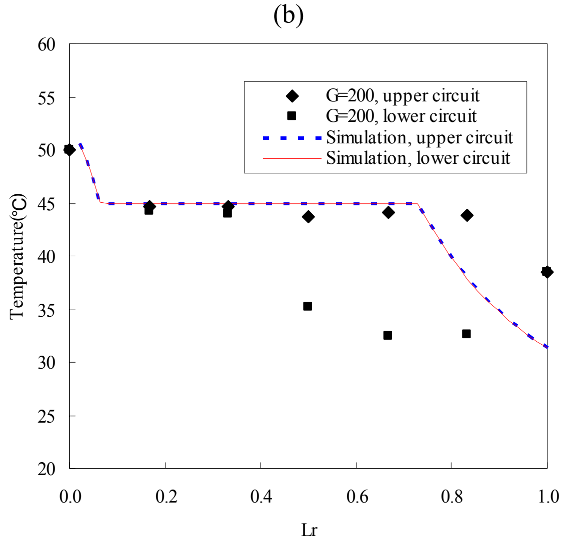
In Table 2, the first point of 'o' at a given refrigerant flow rate is the critical air velocity at which the gravity effect is first noticed in numerical calculation. Contrary to the refrigerant flow rate, the gravity effect develops further as the air flow rate increases. Once the critical conditions appear, the state of refrigerant flow with greater air velocities will be in the gravity-affected region.



(a)

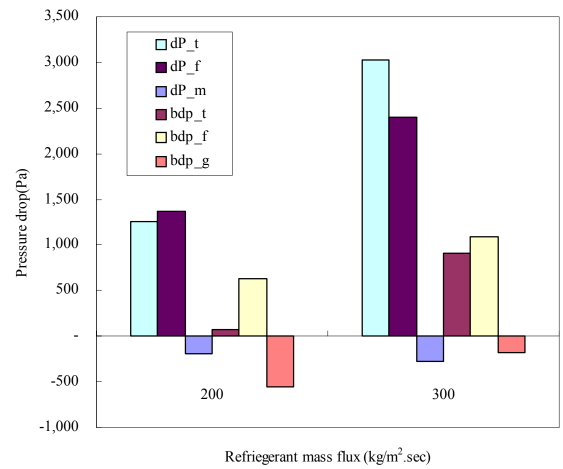


(b)

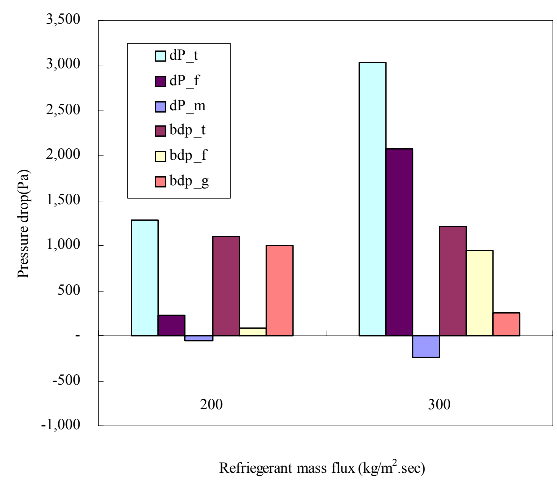


(c)

Fig. 3 Test data of Wang et al.(1999) and simulation results for wall temperatures along the refrigerant (R-22) path; (a) test data at mass flux of 300 kg/m^2.s and simulation with gravity effect; $V_{a,i}$ = 1.0 m/s, $T_{a,i}$ = 25 °C, $T_{c,i}$ =45 °C, $T_{r,i}$ = 50 °C, (b) test data at mass flux of 200 kg/m^2.s and simulation with gravity effect: $V_{a,i}$ = 1.0 m/s, $T_{a,i}$ = 25 °C, $T_{c,i}$ = 45 °C, $T_{r,i}$ = 50 °C, (c) test data at mass flux of 200 kg/m^2.s and simulation without gravity effect: G=, $V_{a,i}$ = 1.0 m/s, $T_{a,i}$ = 25 °C, $T_{c,i}$ = 45 °C, $T_{r,i}$ = 50 °C,



(a)



(b)

Fig. 4 Simulation results for pressure drops; (a) the upper 'n' type circuit, (b) the lower 'U' type circuit; $V_{a,i}$ = 1.0 m/s, $T_{a,i}$ = 25 °C, $T_{c,i}$ =45 °C, $T_{r,i}$ = 50 °C, R-22.

Table 2 Observation of the gravity-affected region

Refrigerant flow rate (kg/h)		20	25 G=100	30	40	50 G=200	60	70	75 G=300	80	90
Air velocity (m/s)	0.1	NA									
	0.2	NA	NA								
	0.3	NA	NA	NA							
	0.4	NA	NA	NA	NA						
	0.5				o						
	0.6										
	0.7					×					
	0.8					o					
	0.9						×				
	1.0						o				
	1.1										
	1.2										
	1.3										
	1.4							×			
	1.5							o	×		
	1.6								o		
	1.7										
	1.8									×	
	1.9									o	
	2.0										×
	2.5										o
	3.0										

CONCLUSIONS

Gravity effect has been calculated and detected using 'nU' type circuit condenser. In a fin and tube condenser with horizontal tubes, gravitational pressure drops occur mainly in the U-bend tubes. The gravitational pressure drop becomes dominant when the proportion of the frictional pressure drop is small owing to a low refrigerant mass flow rate and the recovery of momentum pressure drop that compensates for the frictional pressure drop effectively in the higher air velocity.

The conclusions of this study can be summarized as follows.

1. The gravity effect can be simulated with considering gravitational pressure drop in U-bend tube, and be detected using 'nU' type circuit condenser.

2. The gravity effect is a function of both the refrigerant flow rate and the air velocity.

3. The critical air velocity and the critical refrigerant flow rate, which are starting points of the gravity effect, can be determined for each set of condenser operating conditions.

4. Those critical values can be illustrated in a table with rows of air velocities and columns of refrigerant flow rates. The table provides a guideline as to whether a particular set of operating conditions will result in a gravity-affected region or not. And the table also will be useful for the specific purpose of application like control programming of condenser operation.

ACKNOWLEDGMENTS

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NOMENCLATURE

bdP	Pressure drop in U-bend tube [Pa]
g	Gravitational acceleration [m/s^2]
G	Mss flux [kg/m^2.s]
H	Height [m]
L	Length [m]
Lr	Relative length ratio
P	Pressure [Pa]
T	Temperature [°C]
v	Specific volume [m^3/kg]
V	Velocity [m/s]
x	Quality

Greek symbols

ΔP	Pressure drop [Pa]
α	Void fraction
λ	Directional flag(-1 or 1)
ρ	Density [kg/m^3]

Subscript

a	air
b	U-bend
c	condensation (saturated state)
f	frictional
g	gravity
i	inlet, index
l	liquid
m	momentum
r	refrigerant
t	total
v	vapor or gas

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