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An experimental study of the flow phenomena of R134a flowing through a capillary tube

Jatuporn Kaew-On[a,d]
[a] Physics Department , Faculty of Science, Thaksin University, Papayom, Phattalung 93110, Thailand
kaew_on@yahoo.com

Kitti Nilpueng[b,d]
[b] Mechanical Engineering Department, Faculty of Engineer -ing, South East Asia University, Bangkok 10160, Thailand
Nilpueng@yahoo.com

Sakkarin Chingulpitak[c,d]
[c] Joint Graduate School of Eneigy and Environmenl (JGSEE), King Mongkut's University ol Technology Thonburi, Bangmod, Bangkok 10140, Thailand
e_deaw@hotmail.com

Somchai wongwises[d,*]
[d] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Mechanical Engineering Department, Faculty of Engineering, King Mongkut's University of Technology Thonburi. Bangmod, Bangkok 10140, Thailand
somchai.won@ kmutt.ac.th

ABSTRACT
In the present work, the flow phenomena of the R-134a flowing through the adiabatic capillary coiled tube are experimentally studied. The main parameters relating flow conditions such as inlet pressure, degree of subcooling mass flow rate, are examined. The test section is made from copper tubing with inner diameters of 1.07mm and the coil diameters of 50 mm. The local pressure and temperature distribution along the length of the capillary coiled tube are measured at several inlet pressures and various degrees of subcooling. The experiments are performed at inlet pressure ranging from 10 to 12 bar, mass flow rate from 9 to 11 kg/hr, and the degrees of subcooling from 6 to 10.5 ºC. It was found that there are three regions of the refrigerant flow inside capillary tube including subcooled liquid region, metastable liquid region, and metastable two-phase region and these are discussed in details.

Keywords: Capillary tube; Adiabatic; Local pressure; R-134a; Metastable.

*Corresponding author. Tel.: +662-470-9115; fax: +662-470-9111

E-mail address: somchai.won@kmutt.ac.th (S.Wongwises)

1. INTRODUCTION

The performance of the spiral capillary tubes have been studied by some researchers, and some examples of the studies are described as follows:

Kim et al. (2002) studied the performance of R-22, R407C and R410A in several capillary tubes for air conditioners. They performed at 40, 45 and 50 ºC of the condensing temperature, and 1.5, 5 and 10 ºC of the degrees of subcooling temperature. They used the Buckingham π theorem to develop the correlation for predicting the mass flow rate through the capillary tube. They concluded that the mass flow rates of R407C were greater by 4.0 %, and those of R410Aa were greater by 23%, than those of R22. The mass flow rates in spiral capillary tube were smaller compared with those of straight, especially, for the cases of smaller the coiled diameter. The deviation of experimental results for R22, R407C and R410A from the dimensionless correlation in this study was between ±12% for all test conditions.

Guobing and Yufeng (2006a,b) studied the performance of coiled adiabatic capillary tubes both theoretically and experimentally. The results were used to compare with the straight capillary data. They found that mass flow rate of the refrigerant substantially increases with increasing the coil diameter. However, little change was observed for coil diameter above 300mm.

Park et al. (2007) studied the flow characteristics of the coiled capillary tubes and to develop a generalized correlation for the mass flow rate through the coiled capillary tubes. The present correlation showed good predictions with the present database for R22, R407C and R410A in the straight and coiled capillary tubes, yielding average and standard deviations of 0.24% and 4.4%, respectively.

Khan et al. (2009) investigated the flow of R-134a inside an adiabatic spirally coiled capillary tube. The main parameters such as capillary tube diameter, length, coil pitch, and inlet subcoolings , were studied. They concluded that the effect of coiling of capillary tube reduces the mass flow rate by 5 to 15 percent as compared to those of the straight capillary tube operating under the similar

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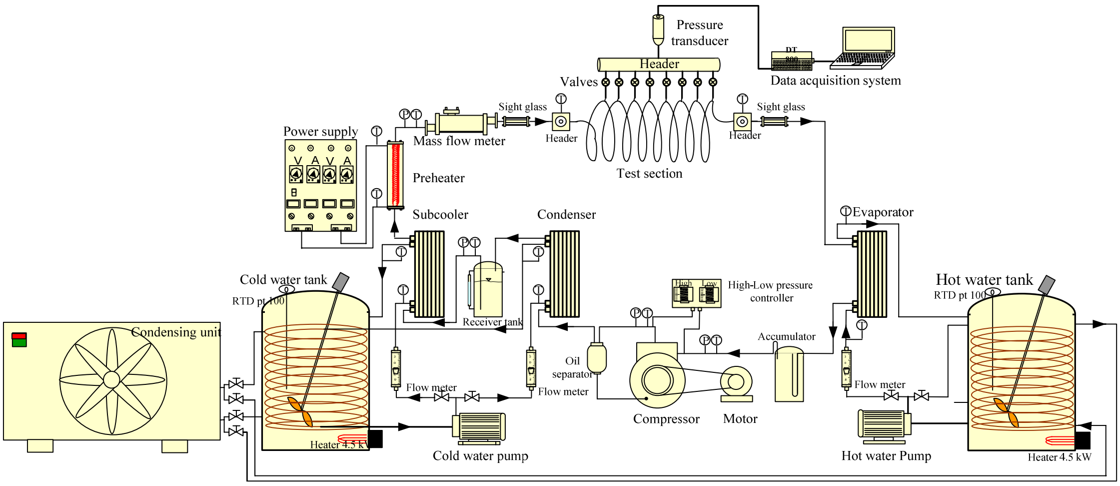

Fig. 1: Schematic diagrams of the experimental apparatus

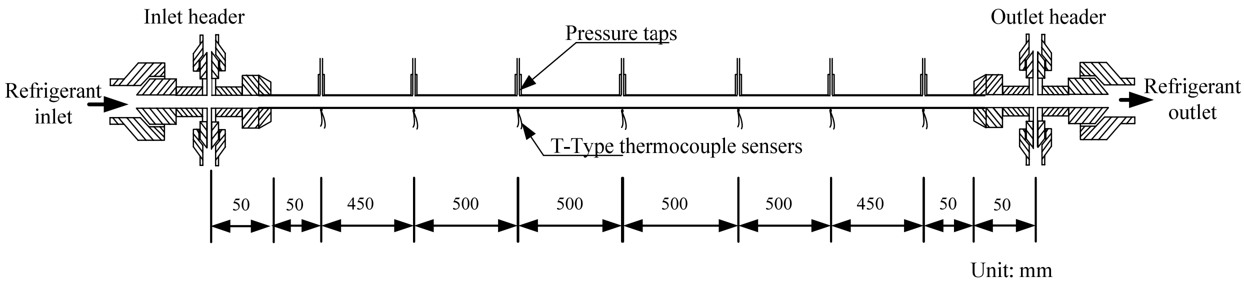

Fig. 2: Schematic diagram of the test section

conditions. They also proposed correlation to predict the mass flow rate in spiral coiled capillary tube. Khan et al. (2009) correlation could predict more than 91 percent of the mass flow rate. The data were in agreement with measured data in an error band of ±10 percent.

Vins and Vacek (2009) presented the two-phase flow of R218 through a capillary tube. They compared the experimental mass flow rate by using two methods: the conventional power law function and (b) an artificial neural network. They found that the average and standard deviation of the correlated data with the power law function are -0.41% and 4.85%, respectively. While, the data obtained from an artificial neural network was more precise with the average and standard deviation of -0.12% and 3.45%, respectively.

Mittal et al. (2010) studied the coiling effect on the flow of R-407C in an adiabatic helical capillary tube. They observed that the coiling capillary tube was strongly effect on the mass flow rate of R-407C through the capillary tube. They also found that the mass flow rates in coiled capillary tube were 5-10 % less than those in a straight one. The correlations based on Buckingham π theorem were developed for predicting the mass flow rate in straight and helically capillary tube. The error band of comparison between experimental data and their correlation was ±10%.

As mentioned above, many previous researchers have studied the flow characteristic of refrigerants inside the capillary tube. However, experimental results for other refrigerants such as R-134a are still lacking. Moreover, the flow phenomena and pressure distribution along the capillary tube length need more information. In the present work, the main concern is to study the main parameters such as the inlet pressure, degree of subcooling on the pressure distribution and mass flow rate.

2. NOMENCLATURE

D	diameter of coil (mm)
d	diameter of capillary (mm)
L	length of the capillary tube (m)
n	number of coil
P	pressure (kPa)
$\dot{m}$	mass flow rate (kW)
T	temperature (˚C)

Subscripts

approx	approximate
in	inlet
out	outlet
sat	saturation

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3. Experimental apparatus and method

The vapour-compression refrigeration system using a capillary tube as an expansion device is setup for this experiment. Fig. 1 shows a schematic diagram of the test facility. It consists of the main refrigeration system component: compressor, condenser, capillary tube, evaporator, and other accessory parts: the oil separator, liquid receiver, filter/drier, sight glass, subcooler and accumulator. A two-cylinder single stage reciprocating compressor, driven by an electric motor, is used to circulate the refrigerant. The speed of the motor is varied so as to provide a wide range of mass flow rates by means of an inverter. The Alco AW-55824 helical oil separator is used to minimize the effect of lubricating oil on the refrigerant flow through capillary tube. The efficiency of oil separation is approximately 99%. Compact plate heat exchangers are used as condenser, evaporator and subcooler.

An electrical heater and a separated refrigeration system are installed in the water tank so as to control the water temperature. The hot water is supplied from a hot water tank by the circulating pump and passes through the flow meter and evaporator. The downstream pressure of the test section is controlled by adjusting the temperature and the flow meter of hot water. The upstream pressure of the test section is regulated by adjusting the temperature of cold water. The degree of subcooling of refrigerant entering the test section is set by varying the flow rate of water to the subcooler. The test runs are chosen to cover a wide range of working conditions of an air conditioner. The upstream pressures are set at 10, 11 and 12 bar, while the downstream pressures are varied between 3.5 to 4.5 bar. The degree of subcooling is varied from 6 to 10.5 ºC.
The pressure distribution inside the capillary tube was measured by the pressure transducer calibrated from 0 to 22 bar within a ±20 mbar accuracy. The T-type thermocouple with an accuracy of ±0.1 ºC was installed to measure the distribution of the temperature along the test section. A total of nine thermocouples are soldered on the outer surface wall of the capillary tube at nine sections along the test tube to measure the outer wall temperatures. These outer wall temperatures will be used to determine the inner wall temperatures based on heat conduction through the wall.The flow rate of the refrigerant through the capillary tube was measured by a coriolis mass flow meter (ABB FCM2000) with an accuracy of ±0.25%.

The details of the dimension of the test capillary tube are presented in Fig.2. The inlet pressure and inlet temperature are measured at the inlet header. Similarly, the outlet pressure and outlet temperature are obtained from the outlet header. Seven points of the capillary tube are drilled for pressure taps installation. Also, the seven T-type thermocouples are installed at the same section of the pressure taps. The thermocouples are insulated with the Aeroflex standard sheet to reduce the effect of heat transfer on the measurement errors. The range of experimental conditions tested in this study is listed in Table 1. The uncertainties of measured quantities and calculated parameters are shown in Table 2.

Table 1: Experimental conditions

Working refrigerants	R-134a
Test section	d = 1.07 mm , D = 50 mm
Mass flow rate, (kg/hr)	9 - 12
Degree of subcooling (ºC)	6 – 10.5 ºC
Inlet pressure (bar)	10, 11, and 12
Outlet pressure (bar)	3.5- 4.5

Table 2: Uncertainty

Temperature	±0.1 ºC
Pressure transducer	±0.1 kPa/m
Mass flow rate of refrigerant	±0.1 % of full scale

4. RESULTS AND DISCUSSION

4.1 Flow phenomena inside the capillary tube

In this study, in order to identify the refrigerant flow phenomena inside the capillary tube, the pressure and temperature distribution along the capillary tube is presented. As shown in Fig.3, it can be seen that the measured pressure is gradually decreased while it is rapidly decreased at the end of the tube. On the other hand, the measured temperature along the tube is nearly constant after that it is suddenly decreased at the end of tube. Considering the relations between the measured and saturation pressure corresponding to measured temperature, it is found that the refrigerant flow inside the capillary tube can be divided into three regions: subcooled liquid region, metastable liquid region, and metastable two-phase region. In subcooled liquid region, the measured pressure is higher than the saturation pressure. However, in the metastable liquid region, it is found that the saturation pressure is nearly constant but the measured pressure is lower than the saturation pressure. The saturation pressure behavior under flashing process indicated that the refrigerant exists in the liquid state. That is, the refrigerant exists in the liquid state although the measured pressure is lower than the saturation pressure which leads to non thermodynamic equilibrium. Therefore, the flow phenomenon in this region is called the metastable liquid flow. In the metastable two-phase region, the measured temperature is suddenly decreased. This is due to velocity of refrigerant is greatly increased when the liquid refrigerant is changed to liquid-vapor mixture which result in a sudden decrease of refrigerant pressure and temperature. In addition, it is also found that the measured is lower than the saturation pressure. As described above, it means that the refrigerant is in the liquid-vapour mixture and the refrigerant does not existed in thermodynamic equilibrium. Under this condition, it is called the metastable two-phase flow. This flow phenomenon is consistence with the results of Garcia-Valladares (2007).

4.2 Effect of operating condition on the refrigerant flow characteristics

4.2.1 Inlet pressure

Figs.4 – 5 show the effect of inlet pressure on the pressure distribution and the mass flow rate. The relationship between the measured and saturation pressure in the

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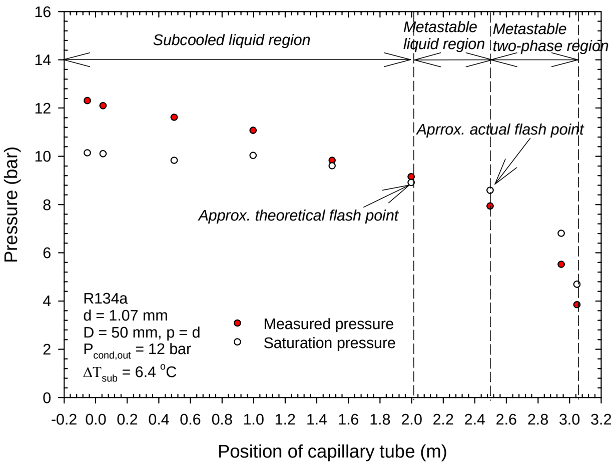
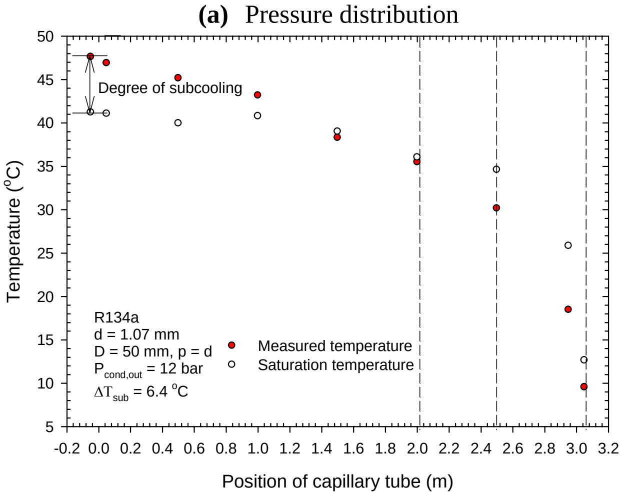
capillary tube at different the inlet pressure is shown in figure 4. It can be seen that the length of subcooled liquid



(a) Pressure distribution



(b) Temperature distribution

Fig. 3 Flow phenomena inside the capillary tube (a) pressure distribution, (b) temperature distribution

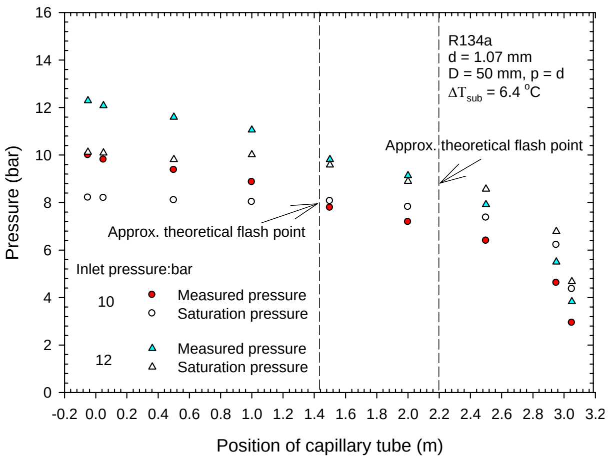


Fig. 4: Pressure distribution at various inlet pressures

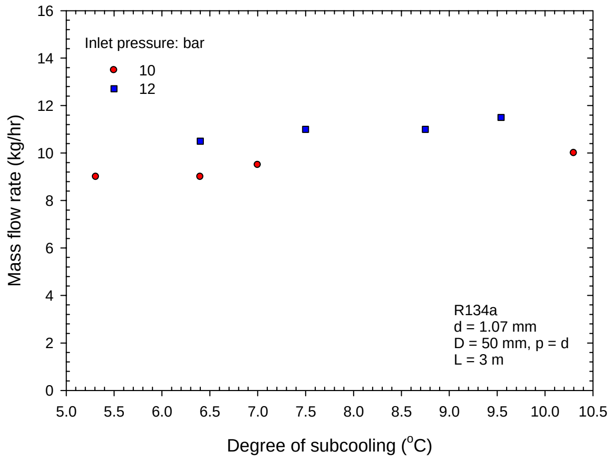


Fig. 5: Effect of inlet pressure on the mass flow rate

region is extended with increasing the inlet pressure. The length rises to 1.4 m, and 2.2 m at the upstream pressures of 10 bar, and 12 bar, respectively. In other words, the results show that the flash point is delayed when the inlet pressure increased. The probably reasons for this behavior are the pressure drop in single-phase liquid flow is not much dependent on pressure, whereas, the pressure drop of the vapor-phase corresponds to a smaller drop in the saturation temperature at high pressure. In addition, at the same the degree of subcooling, a larger pressure drop is necessary to reach saturated conditions at higher pressure. In addition from Fig. 5, it is found that the refrigerant mass flow rate increase as the capillary inlet pressure increase. The increase in the flow rate may be caused by the higher driving force at the inlet of capillary tube when the higher capillary inlet pressure. Nonetheless, it is found that the increase of inlet pressure at constant degree of subcooling results in increased of refrigerant inlet temperature and attributed to the refrigerant mass flow rate decreased due to decrease in upstream liquid density of refrigerant. However, the effect of refrigerant density is less than the effect of the pressure difference which causes the increase of flow rate.

4.2.2 Degree of subcooling

The effect of degree of subcooling on the pressure distribution and the mass flow rate illustrated in Figs.6 and 7. It is found that the theoretical flash point is shifted away from the beginning of the tube when the degree of subcooling is increased. This means that the subcooled liquid region also increased with expanding the degree of subcooling. The length rises to 1.9 m, and 2.2 m at the degree of subcooling of 6.2 °C, and 10.2 °C, respectively. In other words, the increased of subcooling results in delayed of flash point. This means the single-phase section is higher than that of the two-phase section. In the fact that the pressure drop per meter in single-phase is much lower than in two-phase section. Therefore, as given the inlet pressure the mass flow rate increase with increasing of degree of subcooling. As presented in Fig. 7,the mass flow rate is found to increase at the same rate for all conditions

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by about 0.25 kg/h/^{o}C for the increasing of the degree subcooling from 6.2 ºC to 10.2 ºC.

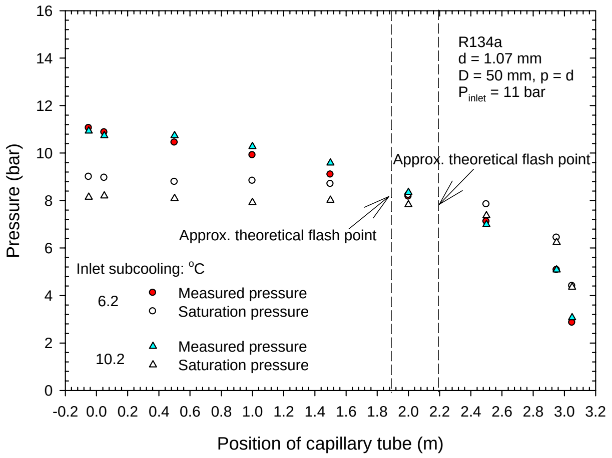

Fig. 6: Pressure distribution at various degrees of subcooling

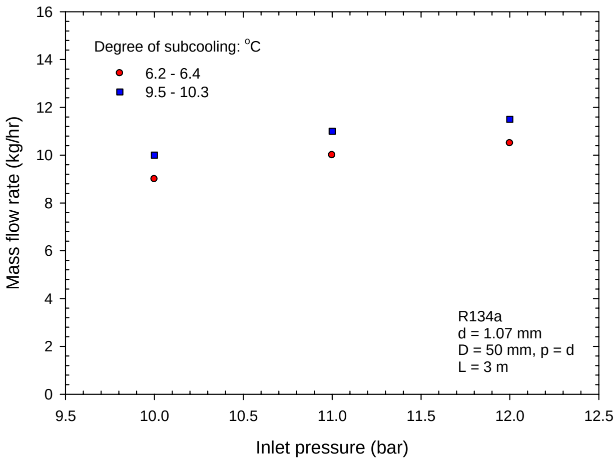

Fig. 7: Effect of inlet pressure on the mass flow rate

5. CONCLUSION

In this work, the flow phenomena of the R-134a through the capillary tube are experimentally investigated. A copper tube with inside diameter of 1.07 mm, coil diameter of 50 mm, and 3 m long, is used as the test section. The pressure distribution and the effects of inlet pressure and degree of subcooling on the mass flow rate are addressed. Conclusions can be drawn as follows:

1. The refrigerant flow inside the capillary tube can be divided into three regions: subcooled liquid region, metastable liquid region, and metastable two-phase region. The subcooled liquid region is extended with increasing the inlet pressure and degree of subcooling.
2. The adiabatic capillary tube show an increase in mass flow rate with the rise in degree of subcooling. In present work, the mass flow rate increase about 0.25 kg/hr ºC. The increase in mass flow rate is attributed to the increased liquid length for high inlet subcooling. This is because the resistance of the liquid flow is less than that of the two-phase flow.
3. At the identical test conditions, the mass flow rate of the refrigerant increases with increasing inlet pressure. This is due to the higher driving force at the inlet of capillary tube at higher capillary tube inlet pressure.

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REFERENCES
Garcia, V. O., 2007, “Numerical simulation and experimental validation of coiled adiabatic capillary tubes,” *Applied Thermal Engineering, Vol. 27,* pp. 1062–1071.

Guobing, Z., and Yufeng, Z., 2006a, “ Experimental investigation on hysteresis effect of refrigerant flowing through a coiled adiabatic capillary tube,” *Energy Conversion and Management , Vol.47,* pp.3084–3093.

Guobing, Z., and Yufeng, Z., 2006b, “ Numerical and experimental investigations on the performance of coiled adiabatic capillary tubes,” *Appl. Therm. Eng, Vol.26,* pp.1106 –1114.

Kim, S.G., Kim, M.S., and Ro, S.T., 2002, “ Experimental investigation of the performance of R22, R407C and R410A in several capillary tubes for air-conditioners,” *In. J. Refrigeration, Vol. 25* , pp. 521–531

Khan, M.K., Kumar, R., and Sahoo, P.K., 2008, “An experimental study of the flow of R-134a inside an adiabatic spirally coiled capillary tube,” *Int.J. Refrigeration,Vol. 31,* pp. 970-978.

Park, C., Lee, S., Kang, H., and Kim, Y., 2007, “Experimentation and modeling of refrigerant flow through coiled capillary tubes,” *Int. J. Refrigeration, Vol. 30,* pp.1168-1175.

Mittal, M.K., Kumar, R., and Gupta, A., 2010, “ An experimental study of the flow of R-407C in an adiabatic helical capillary tube,” *Int. J. Refrigeration, Vol. 33, pp. 840-847.*

Vins, V., and Vacek, V., 2009, “Mass flow rate correlation for two-phase of R-218 through a capillary tube,” *Applied Thermal Engineering, Vol. 29,* pp. 28162823.

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