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Obstructed airflow through the condenser of an automotive air conditioner – Effects on the condenser and the overall performance of the system

S.P. Datta [a], P.K. Das [a,*], S. Mukhopadhyay [b]

[a] Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, 721 302, India
[b] Department of Electrical Engineering, Indian Institute of Technology Kharagpur, 721 302, India

HIGHLIGHTS

- In a stationary automotive air conditioning system, maldistribution is created at the air intake of the condenser.
- Tests were conducted over a range of compressor speed and at different percentage of airflow blockage.
- The nature of the blockage upstream of the condenser also has a significant effect on its performance.
- Due to blockage, the cooling effect and COP of the system deteriorate though the refrigerant mass flow rate increases.

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ABSTRACT

The performance of a cross-flow, microchannel condenser of an automotive air conditioning system (AACS) subjected to the maldistribution of airflow has been studied experimentally. The maldistribution of airflow has been created by placing different upstream screens with uniform, middle, side or peripheral block having 30%, 40% or 50% area blockage and a total of 52 set of experiments were conducted over a wide range of parameters. Infrared imaging was used to assess the deterioration of condenser cooling under blocked condition. Though there has been a significant reduction of the performance of the condenser, the refrigerant flow was observed to increase with the increase of area of blockage. The cooling capacity and COP of the system decreased by 8.16% and 16.8% respectively for an area blockage of 50% compared to the normal operating condition. Effect of side and middle blockage were noted to be more severe while, the peripheral blockage had a minimum effect.

1. Introduction

Fin tube type cross-flow heat exchangers are extensively used as condensers and evaporators in many air conditioning systems. The refrigerant flows through the tube side and exchanges heat with the air flowing through the fin passages. The inherent design of such heat exchangers as well as their installation in the working systems does not always ensure uniform airflow through the whole of the heat exchangers. Further, with the passage of time, the amount of air flowing through such heat exchangers decreases and the distribution of airflow over the tubes becomes different from the design condition. The fin passages may get clogged or damaged and the fan blades can get tilted or twisted. As the airflow reduces with an accompanying increase in its maldistribution, the performance of the unit degrades with an additional demand for the driving power. Often it is required to clean or to replace the components under the extreme cases.

Effect of flow maldistribution on the performance of the heat exchangers in general and on that of the evaporators in particular has been studied by several researchers. Many of the investigations are simulation based and aim to design better distributors for the refrigerant circuit. The reductions in COP [1] and cooling capacity [2,3] due to the maldistribution of refrigerant and air have been captured well by the numerical simulations. It has also been demonstrated that a non-uniform distribution of air can induce non-uniformity in the distribution of refrigerant.

Choi et al. [4] conducted an experimental study on a fin-and-tube evaporator and found that the non-uniform airflow can reduce the cooling capacity up to 6%. Chwalowski et al. [5] measured the non-uniform air velocity on the surface of both V &

* Corresponding author. Tel.: +91 03222 282916; fax: +91 03222 282278.
E-mail address: pkd@mech.iitkgp.ernet.in (P.K. Das).

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I-type multi-circuit heat exchangers and observed the evaporator capacity to strongly depend on the angles between slab of coils and the duct wall. Based on similar measurements on I & A-type heat exchangers, Beller and Kroger [6] observed that the downstream rows of tubes suffered from a higher performance reduction than the first row, due to non-uniform distribution of air velocity and temperature. Timoney and Foley [7] examined the effect of artificially created air maldistribution on a 33 tube single circuit evaporator in an open wind tunnel test section. Surprisingly, they found both the rate and the coefficient of heat transfer to increase in case of maldistribution, if the mean air velocity is kept constant. Jianying et al. [8] experimentally investigated the effects of airflow maldistribution on the performance of an air source heat pump chiller under frosting conditions. Aganda et al. [9] found the performance reduction of a multi-pass evaporator to be as much as 35% at a low air velocity.

Song et al. [10] conducted both experimental investigation and numerical simulation to study the performance reduction of multi-circuit evaporators under airflow maldistribution. Mao et al. [11] observed the rate of heat transfer and the pressure drop through the heat exchanger to be sensitive to the pattern of air velocity. A recent simulation study [12] revealed that the maldistribution of refrigerant through different tubes was mainly due to the header pressure drop and its impact could be reduced by enlarging the outlet header size, increasing the heat exchanger aspect ratio or by reducing the microchannel size.

Efforts have also been made to counter the adverse effect of the maldistribution of refrigerant and air by modifying the design and controlling the refrigerant circuitry. To this end, Domanski and Yashar [13] applied a genetic algorithm based optimization system called ISHED (Intelligent System for Heat Exchanger Design) to optimize refrigerant circuitry in order to compensate the airflow maldistribution. Superheat control is also suggested as a measure to minimize the effect of flow maldistribution by a number of researchers [14–16].

The heat exchangers of an automotive air conditioner are, in general, subjected to a more severe condition of air maldistribution. For such heat exchangers uniform air distribution over the face area is rarely guaranteed due to the restriction in space. It is not unlikely that the face area of the heat exchangers is partially blocked by the neighboring components or simply by structural elements. Over and above, there is a higher risk of fin passage clogging due to the harsh working environment. It may be appreciated that while the clogging of fin passage induces a seemingly uniform blockage of the airflow path, the restricted space, and the presents of the neighboring components and the structural elements induces local blockage and renders the airflow distribution lopsided.

Nonetheless, till date only limited investigations have been made on the performance of the automotive air conditioning system (AACS) under airflow maldistribution. Particularly, very few experimental investigations are available on this topic. Various approaches [17–22] had been taken to simulate the effect of flow maldistribution through the condensers and evaporators of AACS. These simulations primarily predict the performance degradation of typical heat exchangers depending on the working conditions and the exchanger geometry [17,20]. Interestingly, many of the studies indicate that the maldistribution of airflow also induces a maldistribution of refrigerant flow. This may have a significant implication on the performance of the other components and the overall performance of the system [21].

The above review of literature reveals that relatively less number of investigations have been made to study the effect of air maldistribution on the condenser of a refrigeration system. On the other hand, the possibility of air maldistribution through the condenser of an AACS is much greater. It is important to know to what extent the non-uniform and restricted airflow through the condenser of an AACS can affect its performance and can reduce the cooling capacity or increase the power consumption. It is also prudent to have an idea whether the performance of the air conditioning system is sensitive to the blockage pattern. To the best of the knowledge of the authors, no such investigations have been reported particularly for an AACS. Primarily, this has been the motivation of the present work.

The present work reports a comprehensive experimental investigation on AACS with restricted airflow through its condenser. Maldistributions are created artificially, placing screens with blockage of different patterns and magnitude ahead of the condenser face. Two different goals are attempted. Firstly, under various type of airflow restriction, the thermal-hydraulic performance of the condenser is studied in detail. Secondly, efforts have been made to understand the effect of flow restriction through the condenser on the overall performance of the air conditioning system. Though the observed deterioration of the condenser performance is intuitive, the effect of restricted airflow on the other components of the system and the overall system performance is quite interesting to note. It is also interesting to note that the system performance is not only dependent on the magnitude of the blockage but is immensely sensitive to the type of blockage.

2. Experimental facility and procedure

2.1. Experimental facility

The condenser under investigation is the part of a stationary test facility, developed for studying the performance of an automotive air conditioning system. The test facility consists of mechanical components deployed in the automobile itself and uses R134a as the refrigerant. The swash plate compressor, connected to a variable speed drive with a dedicated speed control, can run at different speeds to mimic the operation of the automobile. A large number of additional sensors have been incorporated in the facility for a proper estimation of its performance. To compensate the absence of the Engine Control Unit (ECU) an indigenously developed control system has been devised [23]. This exactly follows the protocol of the ECU to run the air conditioning system. An electric heater is placed inside the duct downstream of the evaporator to create the heat load. A schematic representation of the facility is depicted in Fig. 1 and further details of the facility may be referred from Datta et al. [23].

Both the condenser and the evaporator used in the system are cross-flow, fin-microtube, multi-flow heat exchangers with airflow through the fin side and the flow of refrigerant through the tube side. The condenser used in the test rig has a number of parallel flat tubes connected between two headers of circular cross section as depicted in Fig. 2a. Each of the flat tubes encompasses a number of small rectangular passages. The tubes are arranged between the headers in four passes. From inlet to outlet, the passes contain 14, 7, 6 and 4 numbers of tubes respectively. Between and across the flat tubes air is made to flow through the fin passages with the help of a constant speed fan driven by a 12 V battery, as is also the arrangement in the automobile. The condenser is placed inside a duct for monitoring the airflow through it. The duct consists of an inlet plenum for the smooth induction of air through the condenser. The duct is of 0.58 m $\times$ 0.33 m cross-section so that the face area of the condenser snugly fits inside. The 0.32 m diameter fan which sucks ambient air and throws it through the condenser is placed at the inlet end of the duct. An exit plenum at the downstream of the condenser is also provided for the measurement of local velocity and temperature.