Thermal management of machine compartment in a built-in refrigerator

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Abstract. In general a multi-door refrigerator machine compartment comprises of fan, condenser, compressor, control box, drain tray, and drain tubes. The performance of machine compartment depends upon the efficiency of heat extraction or heat exchange from heat generating components such as condenser and compressor. The efficiency of heat exchange can be improved by addressing two major factors, namely (1) Air bypass and (2) Hot air recirculation. The hot air recirculation in the machine compartment for built-in multi-door refrigerator configuration is the focus of this study. The results from Computational Fluid Dynamics (CFD) simulations show that efficiency of heat exchange for built-in application is lower than that for free-standing configuration. Recirculation of hot air and reduction in airflow are the two major factors which contribute towards the variation in machine compartment performance. The CFD simulations were coupled with Partial Factorial Design of Experiment (DoE) approach to systematically investigate the effect of variables such as (a) side gap and top gap between kitchen cabinetry and the refrigerator, (b) the baffle/flap (i.e. back and bottom of machine compartment) on the performance effectiveness of machine compartment. The results of the simulation provided critical design improvement directions resulting in performance improvement. Furthermore, the CFD simulation results were also compared to test data and the results compared favourably.

1 Introduction

Refrigerator machine compartment comprises of compressor, condenser, fan and many other module sets [1-2]. The components and their arrangement must be designed to improve the cooling, structural and noise performances of the refrigerator. A typical multi-door refrigerator machine compartment is as shown in Fig. 1. The overall performance of a refrigerator depends on the compressor and condenser heat dissipation or exchange from the system during operation [3]. In addition, the performance of machine compartment depends on the refrigerator installation configuration (i.e. free-standing or built-in configuration). In general, the depth of a free-standing multi-door refrigerator is approximately double that of built-in multi-door refrigerator. When a free-standing multi-door refrigerator is installed as a built-in configuration, the multi-door refrigerator typically does not perform well, resulting in compressor tripping due to heat-up of compressor. To provide installation flexibility and a greater customer choice, it is important that the machine compartment in a multi-door refrigerator be designed such that the thermal loading of the machine compartment remains within acceptable limits for both free-standing and built-in configurations.

Computational Fluid Dynamics is a well known tool for understanding the flow and thermal behaviour [4-5]. In this study, Computational Fluid Dynamics (CFD)

simulation has been used to investigate the built-in refrigerator thermal dynamics. Visualization of temperature rise inside the machine compartment is critical to understand the thermal loading that exists inside the refrigerator machine compartment.

Fig. 1. Machine compartment architecture with spiral condenser and linear compressor.

The current study was conducted in two phases. For phase-1, CFD simulation was used to investigate the

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performance of multi-door refrigerator for the two installation configuration. The results from these simulations were analyzed to identify the root cause behind the thermal overloading of the machine compartment, particular the compressor. For phase-2, CFD simulations were coupled with a Partial factorial Design of Experiments (DoE) to assess the impact of various parameters on the thermal performance of the machine compartment.

2 Modelling methodology

2.1 Description of multidoor refrigerator

Generally, free-standing and built-in refrigerators are multi-door, in which evaporators are placed in compartments which are covered so as to have a unique aesthetic look. Fan allows the warm air to flow over the evaporator from compartments to lower the temperature and dehumidify it. The remaining components of cooling systems such as condenser and compressor are placed at back and bottom side of the refrigerator compartment called as machine compartment. The machine compartment also consists of the fan for forced cooling. In built-in, the multi-door refrigerator is positioned inside kitchen cabinetry. The warm air passage in built-in refrigerators is important to model as it affects the performance and energy efficiency.

2.2 Assumptions

The following assumptions are made in this study:

- Convective temperature profiles are considered for the freezer and refrigerator compartments,
- Constant temperature profiles are considered for condenser and compressor,
- Steady state condition is assumed for simulation,
- Boussinesq assumption is used to model the buoyancy effects,
- The flow is assumed to be turbulent and Spalart Allmaras turbulence model is used,
- Fluid flow is assumed to be incompressible.

2.3 Fluid or CFD model

Fluid modeling was carried out in Creo 3.0 using the master assembly of multi-door refrigerator. The freezer and refrigerator compartment fluids are modelled as void, but the refrigerator structure that are body and door are modelled as solid structure. The compressor and condenser are modelled as void and the fan is modelled as rotating fluid domain considering Moving Reference Frame (MRF) methodology. The base plate and back plate are modelled as solid domains whereas the machine compartment air is modelled as fluid domain. Surrounding air is assumed as ambient fluid domain. For built-in configuration, the kitchen cabinetry is also modelled. Fig 2 shows the CFD model for free-standing and built-in configurations.

The fluid model is meshed using Fluid-Nexus version 1.5.4 software. The material properties used in this study are summarized in Table 1. The boundary conditions used in this study are tabulated in Table 2. The commercial CFD solver, Acusolve version 13 is used for the CFD simulations and the solver settings used in this study are summarized in Table 3.

Fig. 2A. Typical CFD model for free-standing and built-in.

Fig. 2B. Locations where the simulation data extracted.

Fig. 2. Fluid/ CFD model.

Table 1. Material properties.

	Plastic	Al	Foam
Density, ρ (kg/m ³)	1021.5	2658	32
Sp. Heat, C_p (J/(kg-K))	960	998	500
Conductivity, k (W/(m-K))	0.16	235	0.018
	Gasket	Steel	Air
Density, ρ (kg/m ³)	20	7850	1.185
Sp. Heat, C_p (J/(kg-K))	960	449	1005
Conductivity, k (W/(m-K))	0.06	72.8	0.0233
Viscosity, μ (kg-m/s ²)	--	--	1.6E-05

Table 2. Boundary condition details considered for simulation.

Location	Boundary condition type
Freezer compartment	Convective wall
Refrigerator Compartment	Convective wall
Ambient domain	Convective wall
Condenser coils	Weighted average const. temp

Table 3. Acusolve Solver Settings.

	Mode	steady-state
Equation	Flow	Navier Stoke
	Temperature	Advection Diffusion
	Radiation	Enclosure
	Species	None
	Turbulence	Spalart Allmaras
	Mesh	Eulerian
Solution	num_krylov_vectors	70
	Relaxation	0.3

3 Result and discussion

3.1 Phase 1

To identify the performance variation of same multi-door refrigerator between two different installing conditions through Computational Fluid Dynamics (CFD) simulation, parameters like the flow rate, the heat exchange from condenser-compressor and the air temperature before fan inlet data are extracted. The data are summarized in Tables 4 and 5. For a better insight, the temperature contour on a plane passing through the machine compartment and temperature streamline are captured as shown in Fig 3 and 4.

Through the CFD simulation of Phase1, it is observed that, the total flow rate for built-in configuration is reduced by 8% as compared to free-standing, as the flow passage around the refrigerator in built-in got reduced. The total heat exchange for built-in configuration is reduced by 45% as compared to free-standing configuration, which can be attributed to high inlet temperature (as hot air recirculation observed) and less flow rate. The compressor heat exchange seems to be similar in both situations as compared to condenser since compressor is always surrounded by hot air.

3.2 Phase 2

Based on the Phase1 results, hot air recirculation was identified as the major contributor for the refrigerator performance reduction. To increase the performance of built-in refrigerator, the partial factorial Design of Experiment (DOE) is considered with following performance affecting variables with the ranges as shown in Table 6.

Table 4. Normalized flow rate details.

Normalized Flow Rate [cfm]						
	Total	Back Inlet	Bottom Inlet	Front Inlet	Back Outlet	Front Outlet
Free Standing	100.0	55.77	31.03	14.2	79.02	20.98
Built-in	91.84	48.58	25.43	18.3	70.35	21.49

Table 5. Normalized heat exchange and average temperature of plane before fan inlet.

Normalized Heat Exchange [W]				Normalized Avg. Temp @ fan front plane [°F]
	Condenser	Compressor	Total	
Free Standing	72.04	27.96	100.00	100.00
Built-in	33.16	22.16	55.34	107.94

Free standing

Built-in

Fig. 3. Temperature contour on plane passing through the machine compartment.

Free standing

Built-in

Fig. 4. Temperature contour with streamline.

Table 6. DoE variables.

X's	Factors	-	+
X1	Back flap	-	+
X2	Side restriction	-	+
X3	Top restriction	-	+
X4	Bottom flap	-	+
Y's	Factors		
Y1	Airflow over condenser fan (cfm)		
Y2	Overall heat exchange (W)		
Y3	Average temperature at compressor (°F)		

As per the partial factorial DOE, eight cases were considered for simulation. Case details are summarized as in Table 7. Flowrate, heat exchange from compressor-condenser and the temperature at fan inlet results are tabulated in Tables 8 and 9.

Fig. 5A. Representing top restriction.

Fig. 5B. Representing side restriction.

Fig. 5C. Representing back and bottom flaps.

Fig. 5. DOE variable schematic representation.

Table 7. DoE case details.

	Back flap	Side restrictions	Top restrictions	Bottom flap
Run 1	-	+	+	-
Run 2	-	+	-	+
Run 3	-	-	+	+
Run 4	-	-	-	-
Run 5	+	+	+	+
Run 6	+	+	-	-
Run 7	+	-	+	-
Run 8	+	-	-	+

Table 8. Partial DOE flowrate details in cfm (change over the Phase 1 built-in configuration).

	Total	back inlet	bottom inlet	front inlet	back outlet	front outlet
Run 1	1.04	1.52	-0.87	0.24	1.88	-1.21
Run 2	0.79	2.51	-1.02	-0.85	2.12	-1.78
Run 3	0.01	2.57	-1.33	-1.38	1.67	-1.87
Run 4	0.43	1.07	-0.91	0.12	1.58	-1.29
Run 5	-5.18	-2.12	-1.68	-1.54	-3.68	-1.82
Run 6	-1.91	-2.23	-0.15	0.31	-1.67	-0.77
Run 7	-2.24	-1.80	-0.89	0.30	-1.57	-1.00
Run 8	-5.13	-1.55	-2.43	-1.30	-4.01	-1.69

Table 9. Partial DOE heat exchange and average temperature of plane before fan inlet (change over the Phase 1 built-in).

	Heat Exchanged [W]			Avg. Temp @ fan front plane [°F]
	Total	Condenser	Compressor	
Run 1	-1.38	-0.06	-1.31	-0.10
Run 2	6.94	6.82	0.12	-2.07
Run 3	4.84	5.34	-0.49	-1.99
Run 4	1.28	1.90	-0.61	-0.65
Run 5	20.39	20.02	0.37	-8.67
Run 6	10.45	10.61	-0.15	-4.45
Run 7	10.22	10.14	0.08	-4.07
Run 8	19.11	19.01	0.11	-8.38

3.3 Parametric study

CFD data from Tables 8 and 9 are evaluated using the statistical JMP software to find the effectiveness of each variable against the Y's mentioned in Table 6. It is observed that, the total airflow varies with delta variation of 6.22 cfm, total heat exchange varies with delta variation of 20.47 W and average temperature at fan front plane varies with delta variation of 8.57 °F. Also, the fit model analysis for each variable against Y's are also plotted.

3.3.1 Effect on total airflow

The total airflow fit model analysis is shown in Fig 6. The major variation in the total airflow is coming from back flap and the bottom flap. Total airflow of machine compartment got reduced by 11% and 7% because of back flap and bottom flap. Top and side restrictions are having negligible effect on total airflow.

Fig. 6A. JMP normal plot for total airflow.

Fig. 6B. Fit model analysis for total airflow.

Fig. 6. Fit model analysis for total airflow.

3.3.2 Effect on total heat exchange

The total heat exchange fit model analysis is shown in Fig 7. The major variation in the total heat exchange is coming from back flap and the bottom flap. The total heat exchange in machine compartment is increased by 35% and 20% because of the back and bottom flap respectively. Top and side restrictions are having negligible effect on total heat exchange.

Fig. 7A. JMP normal plot for total heat exchange.

Fig. 7B. Prediction profile of each variable for total heat exchange.

Fig. 7. Fit model analysis for Total heat exchanged.

3.3.3 Effect on average temperature at fan front plane

The average plane temperature fit model analysis as shown in Fig 8. The major variation in the average

temperature at fan front plane is coming from back flap and the bottom flap. The average temperature at fan front plane is reduced by 5% and 3% because of the back and bottom flap respectively. Top and side restrictions are having negligible effect on average temperature at fan front plane.

Fig. 8A. JMP normal plot for total average temperature at plane before fan inlet.

Fig. 8B. Prediction profile of each variable average temperature at plane before fan inlet.

Fig. 8. Fit model analysis for average temperature of plane before fan inlet.

3.4 1D energy simulation

1D energy simulation with and without flaps were performed. The data of 1D simulation is summarized in Fig 9. Through 1D simulation data it is observed that the refrigerator in built in application with current condition (i.e without flaps) is not recommended, as it generates 75% of hot air recirculation at inlet of machine compartment. Due to this, the compressor temperature increases over the operating limit. The proposed changes reduces the hot air recirculation from the original 75% down to 26%, which provides 20% energy benefit and allows the system to operate back within the allowable range of the compressor.

3.5 Field test

1D From overall simulation study it was observed that, the built-in refrigerator with flaps can prove to be an

efficient option for improved performance. Thus, testing was performed on built-in multi-door refrigerator with bottom and back flaps using field condition where operating conditions are cyclic in nature. The test data is summarized in Table 10. From the testing, refrigerator with flaps shows following improvements:

- Average freeze compartment (FC) temperature colder by 0.4 °F
- Average refrigerator compartment (RC) temperature colder by 2 °F
- Condenser in temperature: colder by 14 °F
- Condenser out temperature: colder by 7 °F
- Compressor temperature is less than the operating limit so tripping would be avoided
- Compressor run time: 2.5% less
- Energy consumption: 4% improvement

Product characteristic	Unit	Difference
RC temp	[F]	-0.4
PN temp	[F]	-0.2
FC temp	[F]	-0.3
IB temp	[F]	-0.3
FC evap temp	[F]	-1.2
RC evap temp	[F]	-3.7
FC cond temp	[F]	-21.3
RC cond temp	[F]	-33.0
Deck air flow	[CFM]	-6.1
FC power	[W]	-4.9
RC power	[W]	-17.7
FC run time	[%]	-5.7%
RC run time	[%]	-6.0%
Total run time	[%]	-11.7%
Test energy	[kWh/day]	-22.4%
Total energy consumption	[kWh/day]	-19.8%

Fig. 9. 1D energy simulation data: Difference between without and with flaps.

Table 10. Normalized test data with and without flaps.

Case	Avg. FC Temp [°F]	Avg. RC Temp [°F]	Condenser In Temp [°F]	Condenser Out Temp [°F]
Refrigerator with flaps	0	31.8	150.84	102.56
Refrigerator without flaps	0.4	33.7	164.84	109.4
Case	Energy Consumption [kWh/day]		Compressor On Time [%]	
Refrigerator with flaps	0.96		0.98	
Refrigerator without flaps	1.00		1.00	

4 Conclusions

The study compares the performance of the multi-door machine compartment in free-standing and built-in configurations. The study includes the parametric study which proved to be an effective tool to show the effect of various parameters on performance of machine compartment in built-in situation.

The results from the CFD show that the performance of machine compartment in built-in configuration is negatively impacted and there is need to study this aspect. From the overall DOE analysis it is observed that, the back flap and the bottom flap have a major impact on the amount of heat exchange and on the temperature at the fan front. Due to flaps, the efficiency of built-in refrigerator machine compartment is increased by around 35% thereby increasing almost 50% of fresh air intake at fan inlet. Also, the condenser out temperature is reduced by around 20%. Thus, the proposed flaps in built-in refrigerator provide to be efficient since the operating condition seems to be in controlled working condition of compressor and temperature overshoot could be avoided to a large extent.

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