One of the world largest autoclave facility – High-precision composite curing oven for Boeing 787 Dreamliner

In May 2015, Kawasaki installed an autoclave facility designed to meet the specification requirements of the Boeing 787-10 at Nagoya East Plant. This facility is identical in diameter to the autoclave (designed for the Boeing 787-8 and 787-9) installed at Nagoya North Plant in 2007. The increased length of the 787-10, however, requires some relater structural changes such as strengthening in some area. This called for further performance improvement in terms of temperature distribution inside the oven. Kawasaki used thermohydraulic analysis and other approaches to optimize the specifications and operating conditions, and achieved uniform temperature distribution with the world's largest-class autoclave.

Preface

Today, structural parts made of composites are being increasingly adopted in various fields, including the aerospace and automobile industries, to meet the growing needs for further weight saving. The increased use of composites has given rise to the need for higher-quality parts and processes. Production of composites entails a firing process; in order to achieve high-quality firing with a large composite structure like an aircraft, an autoclave capable of high-precision pressure control and uniform temperature distribution is necessary.

1 Background

The Kawasaki Group has participated in the international project to develop the Boeing 787 airplane shown in Fig. 1 from the outset. It is responsible for developing and manufacturing the forward fuselage, fixed trailing edge, and main landing gear wheel well (Fig. 2) —all critical components of the airplane. The forward fuselage in particular is unique in that it is molded in one piece from composites. In 2007, an autoclave facility designed for the Boeing 787-8 and 787-9 was installed at Nagoya North Plant. With further ramp-ups and the start of production of the 787-10 around the corner, a new autoclave facility that is the one of the world largest was built at Nagoya East Plant to boost production capacity. Given the increased length as well as thickness of the composite structure to

Fig. 1 The Boeing 787 Dream liner family

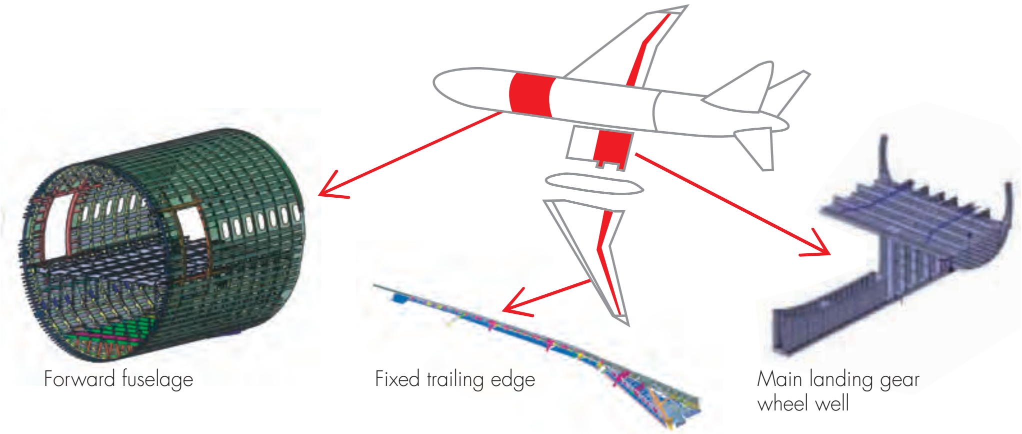


Fig. 2 Sections of the Boeing 787 family supplied by Kawasaki (sections in red)

be molded for the longer variant, the conditions that needed to be overcome were even more stringent than for the previous autoclave.

2 Manufacturing process of the forward fuselage

The forward fuselage is manufactured as a composite component molded in one piece, according to the following procedure.

① Pre-preg lamination

An automated fiber placement (AFP) machine is used to lay up prepreg carbon fiber material, bundled into a certain width and in a precured pliable state, around a huge core (fuselage mold) with the same diameter as the aircraft.

② Curing

The composite layup is placed inside an autoclave to be cured by chemical reaction under high temperature and pressure. Figure 3 shows the cured forward fuselage being taken out of the autoclave.

③ Cutting the outer periphery and drilling holes

Special equipment is used to cut the edges and window openings and drill holes for inserting bolts.

3 Autoclave facility

(1) Required specifications

The autoclave needs to be able to consistently produce high-quality products out of a workpiece that is the world's largest class in terms of both inner diameter and length. Achieving this requires a capability to precisely follow a

Fig. 3 Forward fuselage cured in an autoclave

Table 1 Equipment specifications

Autoclave vessel	Outer diameter (m)	9
	Length overall (m)	30
	Weight (ton)	920
	Material	SFVC2A, SB480
	Applicable regulation	Class–2 pressure vessel

fixed temperature and pressure pattern so that uniform curing is achieved with even strength throughout the structure. The autoclave also must be able to perform two operations a day.

(2) Design specifications

The design specifications shown in Table 1 were adopted in order to fulfill the required specifications. Inside the main unit of the autoclave, which is designed as a pressure vessel, the gas filled inside the vessel is heated and cooled using a heater and coolant, then the gas is circulated with a fan as the workpiece stored inside the muffle furnace (internal cylinder) is fired. The overall flow is shown in Fig. 4. Circulation. The gas blown out from the fan passes along the outside of the muffle furnace and reflects off the outer wall of the door. Then it is led inside the muffle furnace through a screen that regulates the flow. The gas passes through the workpiece, cooler, and heater before being drawn in by the fan and circulated.

The gas filling the autoclave was enriched with nitrogen for increased stability and safety of the molding process. For this reason, a membrane-separation nitrogen generation process was introduced.

The main unit of the autoclave is shown in Fig. 5.

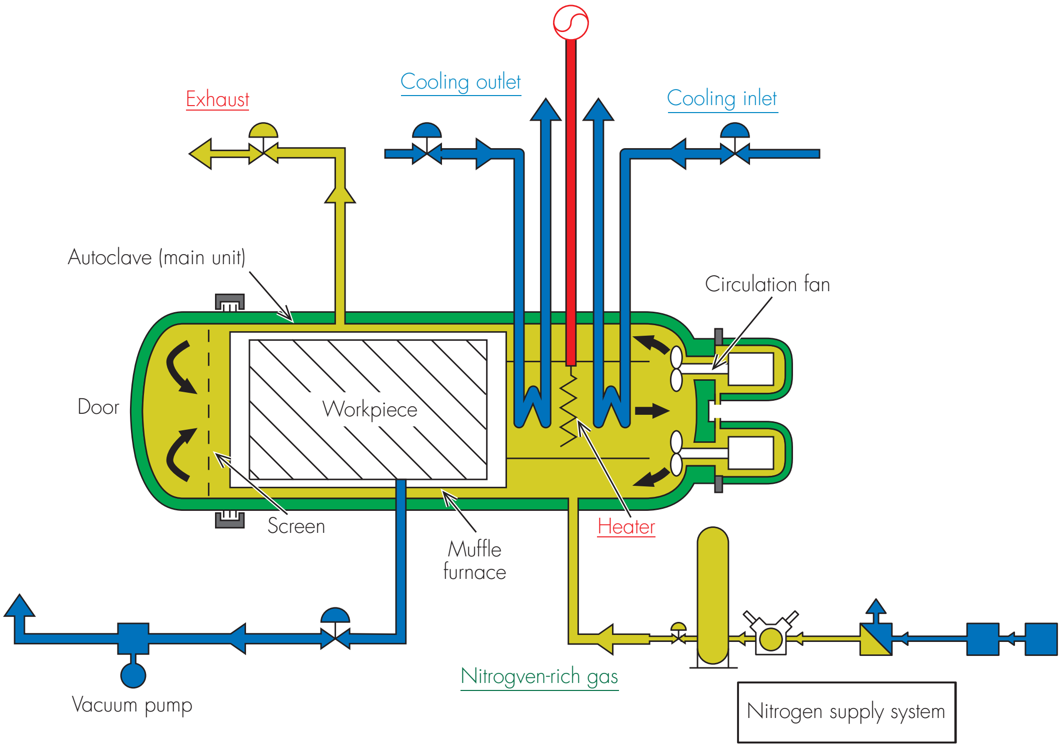


Fig. 4 Overall flow

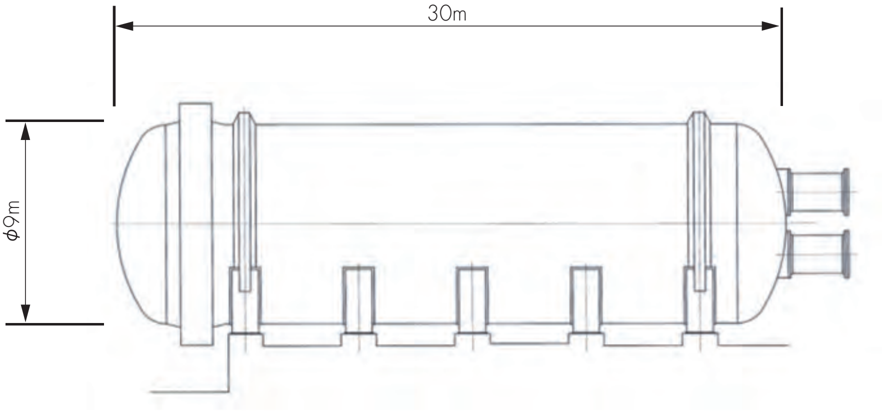


Fig. 5 Main unit of autoclave

(3) Operation pattern of the autoclave

The autoclave is operated in the following process. An example of the temperature and pressure control pattern is shown in Fig. 6.

(i) Pressurization process

The workpiece is placed inside the autoclave, and the door is closed and sealed tight. Then the circulation fan is turned on to start circulating the internal gas.

Next, pressurized nitrogen gas is supplied inside the autoclave, adjusting the pressurization rate with a control valve, until the pressure reaches a fixed level.

(ii) Heating

The heater is turned on, and the output level is adjusted to heat the circulation gas inside the autoclave at a fixed rate. During this process, a thermocouple placed at top center controls the thermocouples mounted in various places of the workpiece so that they are kept within a fixed temperature range for over a fixed length of time.

(iii) Retention and cooling

After a certain length of time has elapsed with the temperature kept within a fixed range, a coolant is drawn regulating the flow to keep the temperature drop at a fixed rate, until the ambient temperature inside the vessel reaches a certain temperature.

(iv) Decompression and ventilation

Once the temperature drops below a fixed point, the pressure inside the vessel is reduced at a fixed rate using a control valve, until it reaches atmospheric pressure. The circulation fan is stopped, and after checking that the oxygen concentration inside the vessel is above a fixed level, the door is opened and the workpiece is taken out.

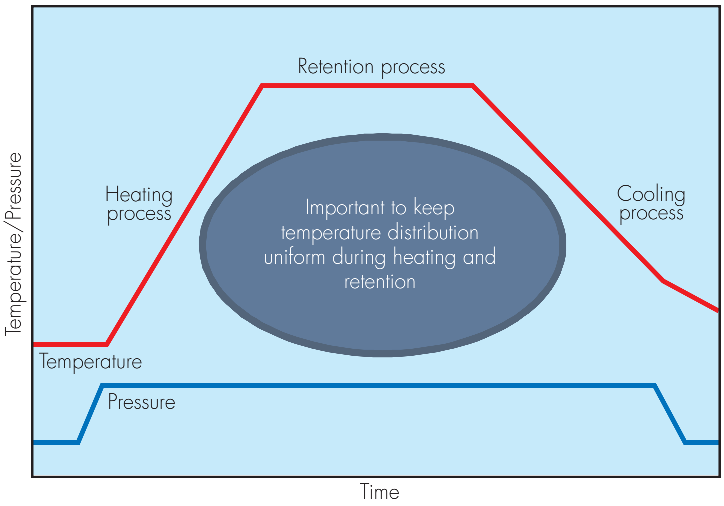


Fig. 6 Control pattern

4 Increasing uniformity of oven temperature

Carbon fiber composites used for airplanes must be cured uniformly so that the strength is kept even throughout the structure. The autoclave used to cure the molded composites must ensure uniformity of temperature in a steady state, as well as in the temperature distribution during temperature rise, and the time taken to reach the prescribed temperature. In order to determine the molding conditions to achieve that capability, the optimal operating method was studied by performing thermohydraulic analysis.

(1) Creating and validating an analytical model for study

The structure inside the autoclave was modeled as in Fig. 7, then simulation was performed under the operating conditions of the existing autoclave to determine the temperature distribution inside the oven. When the results were compared with actual measurement results in representative measurement positions inside an autoclave, a congruence was observed as shown in Fig. 8.

Through an analysis using this analytical model, it was confirmed that the temperature distribution inside the oven can be sufficiently reproduced to study the optimum operating method.

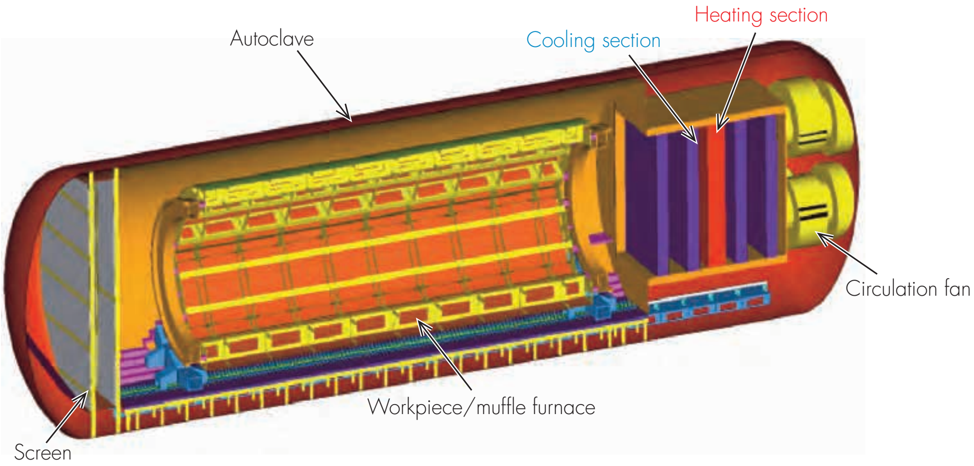
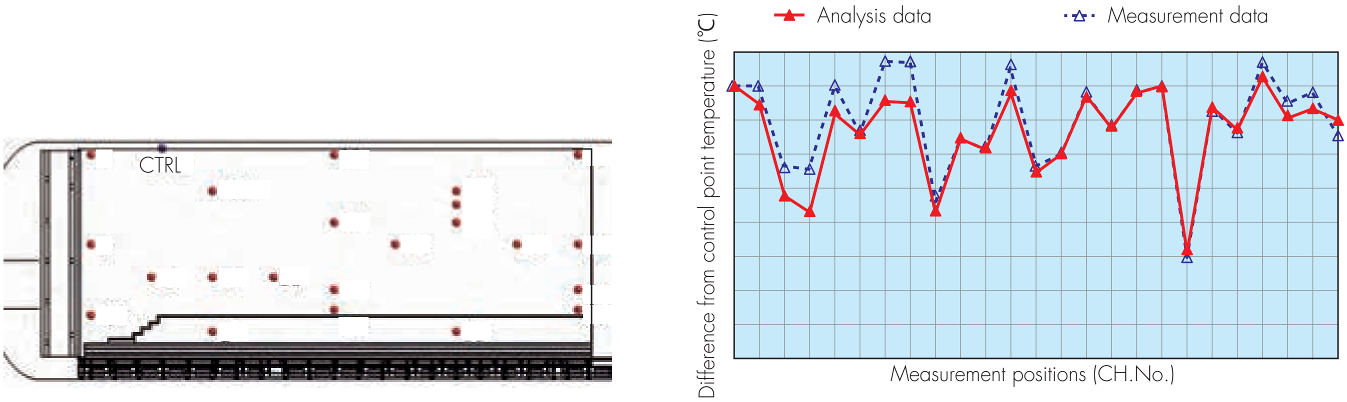


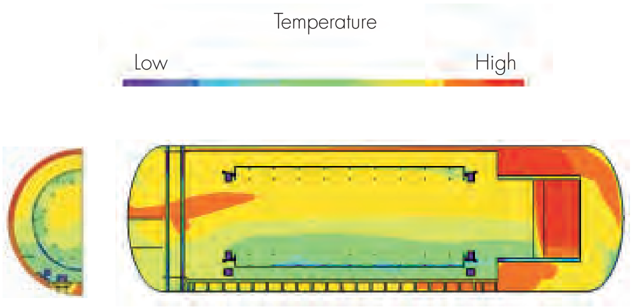
Fig. 7 Analytical model



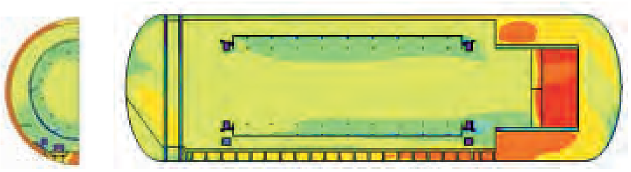
(a) Temperature at each measurement position

(b) Temperature at each measurement position

Fig. 8 Validation of analytical model



(a) Temperature distribution without countermeasure



(b) Temperature distribution with countermeasure

Fig. 9 Comparison of temperature distribution

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(2) Issues in achieving uniform temperature

Due to the structural members (with a large heat capacity) forming the rail laid under the floor of the autoclave for moving workpieces in and out, the temperature under the floor is less responsive to heating. Further, relatively cold air flows out through gaps provided to accommodate thermal expansion on the floor surface for operators to work on. For these reasons, the measurement positions on the bottom side may register lower temperatures. In the new autoclave, we sought to address this issue to achieve an even more uniform temperature distribution.

(3) Countermeasures

(i) Addressing heating issue under the floor with a large heat capacity
① Optimization of the structure of the straightening vanes (screen) for drawing hot gas inside the vessel
② Addition of an auxiliary duct for hot gas
(ii) Reducing the outflow of air from the gaps in the floor surface
③ Reducing the gaps between the floor boards

(4) Verification of the improvements

Analyses were performed to study the three items above and verify their efficacy. Figure 9 shows the temperature distribution during the heating process. Without the countermeasure, gradients are seen in temperature distribution both at the top and bottom. On the other hand, no gradients are seen when the countermeasure is implemented, indicating that a sufficiently uniform temperature is achieved. Thus, we were able to confirm that with the set equipment specifications, heating at a set rate of temperature rise can be achieved while maintaining a uniform temperature distribution under appropriate operating conditions.

With the above study, we were able to confirm that we would be able to manufacture high-quality products under firing conditions that satisfy the required specifications.

Concluding remarks

The autoclave facility examined in this paper was installed at Nagoya East Plant in March 2015, and is now being used for prototyping and process review to prepare for the manufacture of composite parts. By conducting preliminary studies using thermohydraulic analysis and other approaches to examine the equipment specifications and operating conditions, we were able to meet the tough requirement of achieving uniform temperatures inside one of the world's largest autoclaves. We will continue to endeavor to make significant contributions to aircraft production of the Kawasaki Group.