低剪断翼『フルゾーン』を装備した新しいビール酵母タンク

A New Beer Yeast Tank with a Low-shear Impeller, *FULLZONE*

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ビール酵母は，発酵タンクから回収され，何度もビール発酵に使われる。濃厚なスラリーとして酵母タンクに回収された酵母は，所定の温度に冷やされ，その温度で保管される。十分な温度管理がなされないと，酵母の発酵能力が低下し，さらには酵母菌の自己分解を生じることが知られている。この酵母の管理において直面する問題は，次のとおりである。濃厚な酵母スラリーはビンガム流体であり，均一に混合することが容易ではない。その一方で，酵母菌は通常の機械撹拌で損傷を受けるほどに剪断に対して敏感である。

そこで，ビール酵母の混合を改善するため，神鋼パンテツクの撹拌翼であるフルゾーンが取り上げられ，流動シミュレーションと，ベンチテストから実機スケールのテストを通じて，酵母タンク用の撹拌翼として改良された。そして，新たな酵母タンクが設計製作され，現実のビール生産プラントに組込まれた。15ヶ月に及ぶ運転により，この酵母タンクが十分なサニタリー性を有するとともに，次のような改善効果をもたらすことが確かめられた。酵母の死細胞率測定の結果，酵母タンクでの死細胞の増加は無くなった。酵母タンク内の温度分布が一様になった。酵母タンクから発酵タンクに供給する酵母スラリーの濃度が実質的に一定になった。酵母スラリーの速やかな冷却が可能になり，酵母の菌体温度管理も容易になった。撹拌動力は従来翼の1/4以下になった。

Beer yeast is recovered from fermentation tanks and used more than several times. Recovered yeast is stored as thick slurry in yeast tanks, where it is cooled down to a given control temperature to protect the yeast from any degeneration. Encountered difficulties are as follows. Thick yeast slurry is a Bingham fluid of which uniform mixing is not easy. In addition, the yeast cells are so shear-sensitive as to be damaged by mechanical agitation at ordinary impeller speed.

A wide-bladed impeller, *FULLZONE*, was tested to improve yeast tank mixing, and modified through bench-scale to commercial-scale tests and through numerical simulations by CFD. Finally, new yeast tanks were designed and built into an actual beer production process. Its continuous operation for 15 months has confirmed the following improvements and the satisfaction of sanitary requirements. Dead cell counts detected no increase in cell damages in the new yeast tanks. Temperature distribution in the new yeast tanks was uniform. No serious variation in the yeast cell concentration was detected of the slurry supplied from the new yeast tanks to fermentation tanks. Slurry cooling became faster and yeast temperature was more controllable. Impeller power was reduced to less than a quarter of existing yeast tanks.

Key Words :

ビール酵母タンク	Beer yeast tank
攪　　　　拌	Mixing
ビンガム流体	Bingham fluid
流動シミュレーション	CFD
低　剪　断　翼	Low-shear impeller

Introduction

Recent efforts seeking for stable and favourable beer fermentation have found that yeast handling is an essential factor to control beer fermentation and beer quality. After fermentation, yeast cells are settled in the fermentation tank, removed from it, and collected into a yeast tank as thick slurry. The yeast tank cools down the yeast to a given cold temperature without serious delay, and controls the storage temperature precisely. If not, the yeast degenerates and causes autolysis. Then, the yeast tank hopefully supplies the yeast slurry of a constant cell concentration to fermentation tanks, because it makes control of yeast charge amount precise and makes beer fermentation control stable.

Existing yeast tanks employ ordinary impellers, such as side-entering propellers or top-entering pitched blade turbines, for mechanical agitation. Other existing yeast tanks employ gas lift. However, two observations in this study suggest that these existing tanks might be unsatisfactory. One observation is that thick yeast slurry is a Bingham fluid with a high yield stress, 10 to 30 Pa. This means that the uniform mixing of yeast slurry is not easy for the ordinary impellers and gas lift. The other observation is that yeast cells are damaged by the shear stress caused by impeller rotation at ordinary speed. Therefore, medium- and high-speed impellers are not suitable. In addition, strict requirements for cleaning and sanitary of yeast tanks do not allow the use of such gas spargers with several nozzles or many holes that gas lift might be able to bring improved mixing to Bingham fluid.

In chemical processes there are several impellers applicable to Bingham fluid mixing such as helical ribbons, their likes, double motion mixers, horizontal-shaft mixers. However, many of them do not meet the cleaning and sanitary requirements. In these years, wide-bladed and large-sized impellers are successfully applied for mixing in the wide range of viscosity, by chemical industries in Japan. One of these impellers, *Fullzone* of Shinko Pantec, was taken up to improve the yeast tank mixing by Asahi breweries.

1. Requirements of yeast tank

There are five requirements which a new yeast tank system has to fulfil in yeast handling.

(1) Recovered yeast is cooled down without serious delay. While it is stored, the yeast

slurry temperature is controlled within a given accuracy.

(2) The shear stress caused by impeller rotation does not damage the yeast cells to increase dead cells or reduce fermentation activity.

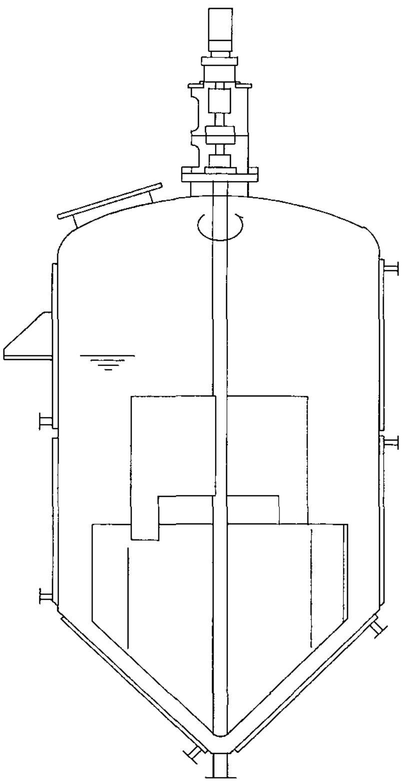
(3) The impeller can mix the yeast slurry so that the discharge from the yeast tank has an almost constant cell concentration from the full level to empty of tank content.

(4) The impeller and tank inside are thoroughly cleaned by ordinary CIP instruments.

(5) The new yeast tank system is free from microbial contamination.

The first three put some limits on impeller speed and impeller size, and the last two restrict impeller structure.

Fig.1 shows a design example of a new yeast tank equipped with a modified Fullzone impeller. The tank has a conical bottom and no baffle plates. The conical bottom comes from easy drainage and from fitting of dimple jacket. Viscous non-Newtonian flow characteristics of yeast slurry allow good mixing without baffles. Additionally, tank cleaning by CIP becomes much easier without baffles. Larger impeller diameter is effective to lower impeller speed or shorten mixing period on the use for yeast slurry of higher concentration.

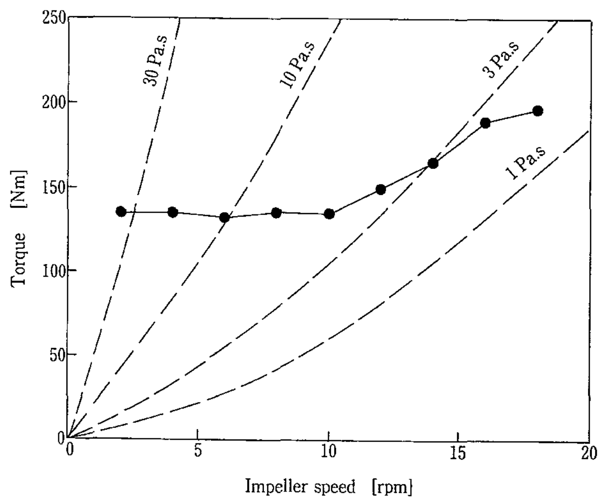


第１図　フルゾーン翼を装備した新しい酵母タンク
Fig. 1　A new yeast tank with Fullzone impeller.

2. Flow characteristics and numerical simulations

Fig.2 shows the data of impeller torque vs. impeller speed, measured in a 5.0m^3 yeast tank with a Fullzone impeller. The measured torque is almost constant in the lower speed range under 10rpm. This is a typical feature of Bingham fluid. The yield stress of this yeast slurry is estimated about 20Pa from the constant torque value. Over 10rpm the impeller torque increases with the increase in impeller speed. This means that the flow condition changes from laminar flow to transition flow. When an enough size of impeller is applied, the transition of flow brings the fluidization of all the yeast slurry in the tank.

In **Fig.2** there are several torque curves for Newtonian fluids different from each other in viscosity. The points where the torque curve of yeast slurry crosses with these curves tell that the apparent viscosity of yeast slurry changes from 2 to 40 Pa.s, depending on

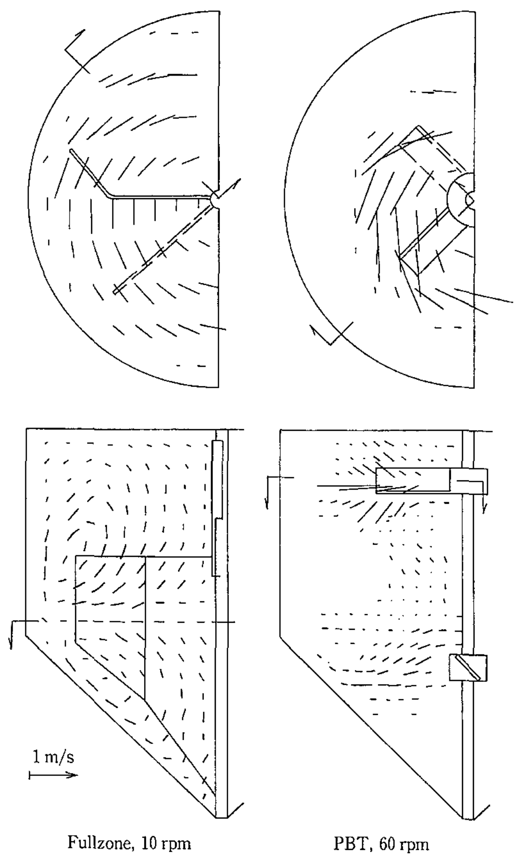


第２図　酵母スラリーでの実測トルク
Fig. 2　Torque measured of yeast slurry.

impeller speed, i.e. shear rate. Thus a relation between shear stress and shear rate for the yeast slurry was derived from the torque data. This relation characterises the viscosity of yeast slurry and makes it possible to simulate the flow in yeast tanks numerically by computational fluid dynamics. It should be noted here that it is difficult to measure the same relation by rotational viscometers. The present authors tried it, but results were erroneously low viscosity values.

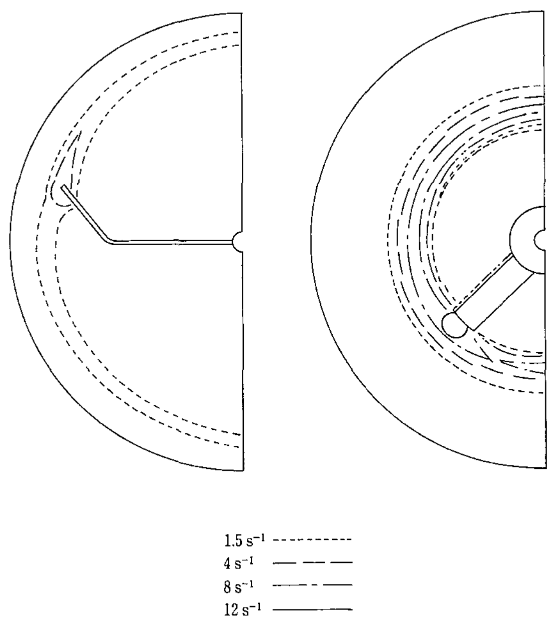
Numerical simulations were done by using a general CFD code and an engineering work station, to solve the flow in two yeast tanks, one for a new tank design utilising a modified Fullzone impeller, and the other for an existing tank design using 2-bladed pitched-blade turbines at two stages. The simulation results are shown in **Figs.3 and 4. Fig.3** indicates flow patterns by velocity vector plots in vertical and horizontal section: Fullzone can move all the slurry in the tan at 10rpm, by vertically and horizontall circulating flow. The pitched blade turbine can hardly move the whole slurry, even a 60rpm. Stagnant regions exist by the tan wall, between the two impellers, and near th bottom. **Fig.4** shows contour maps of shea rate distribution in horizontal sections, unde the same conditions as in **Fig.3**. The pitche blade turbines give the maximum shear rat of $15s^{-1}$ near the impeller tips. Fullzone re duces the maximum shear rate to 1/3 of th pitched blade turbines. The shear rate distr butions together with the velocity vector plot suggest that something like a slipping surfac is formed around the impeller, its diameter i almost same as the impeller diamete Probably, this phenomenon makes yeast tan mixing difficult and requires large impeller for good mixing.

Thus, the numerical simulations of yeas tanks have predicted the followings: existin yeast tanks would not have enough mixin functions to handle the yeast slurry properly Fullzone could improve mixing of yeast slurr as well as decrease the shear stress cause



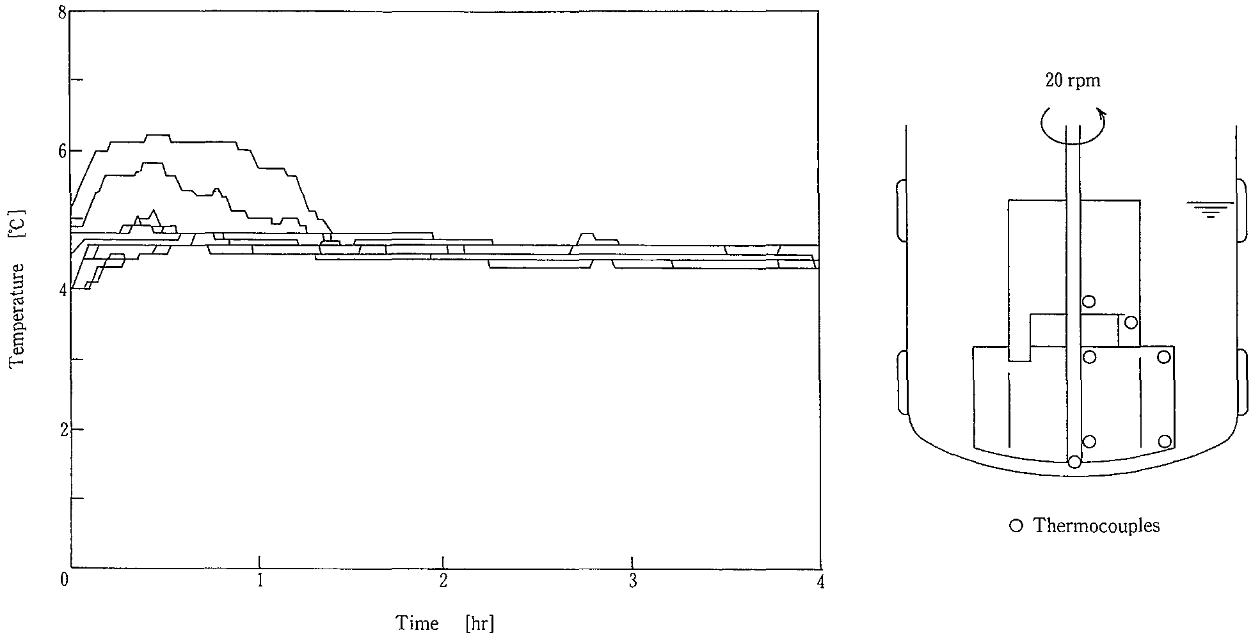
第３図　5m³酵母タンクの流動シミュレーションで得られたフローパターン

Fig. 3 Flow patterns given by numerical simulations of $5m^3$ yeast tanks.

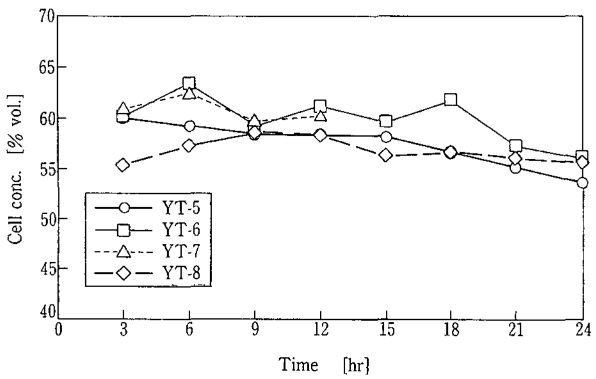


第４図　前図と同一条件の下での剪断速度分布

Fig. 4 Shear rate contours under the same conditions as Fig.3.



第5図　$4m^3$酵母タンクの温度変化
Fig. 5　Temperature differences in a $4m^3$ yeast tank.



第6図　$5m^3$酵母タンクからの排出液中の酵母濃度
Fig. 6　Cell concentration in $5m^3$ yeast tank discharge.

by impeller rotation.

3. Operation results

3. 1 Uniformity of Tank Content

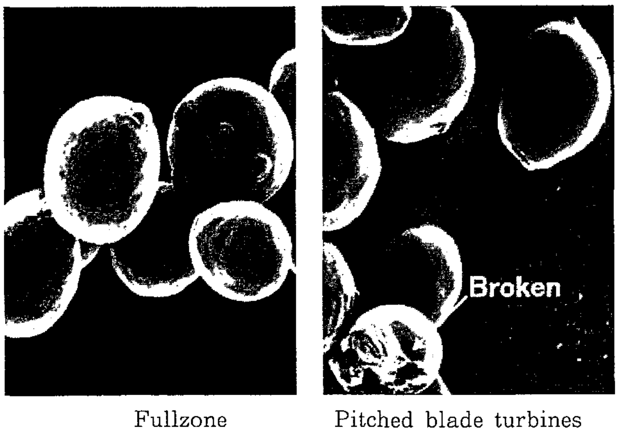
Fig.5 shows a mixing test result. The yeast slurry was settled for 24 hours in a $4.0m^3$ yeast tank without cooling. This caused temperature differences in the tank. Then it was mixed by a Fullzone impeller with its diameter, 60% of tank diameter, and rotated at 20rpm. The upper and lower jackets shown in **Fig.5** were cooled while the impeller was rotated. The temperature differences decreased within 0.4℃ in 1.5 hours. A similar test was tried at 1rpm. Temperature difference about 1℃ remained after 16 hours.

Fig.6 shows another mixing tests by using $5.0m^3$ yeast tanks with Fullzone impellers. The tanks were filled with yeast slurry and mixed for a while. Then, the tank content was discharged at every three hours so as to make the tanks empty for 24 hours. Meanwhile the impellers were rotated intermittently for temperature control and mixing, and stopped to prevent yeast cell damage. The changes in yeast cell concentration were monitored of the discharged slurries. **Fig.6** indicates that the concentration fluctuation for each tank is from 1.7 to 3.5%. The concentration fluctuations measured for the yeast tanks with pitched blade turbines were 8 to 15%, not shown in **Fig.6**.

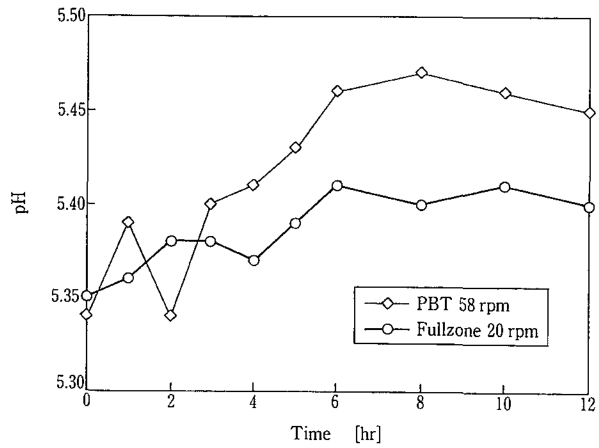
Thus the new design can improve the uniformity of temperature in yeast tanks as well as it decreases cell concentration fluctuation on yeast supply.

3. 2 Effects of Shear Stress on Yeast

After 12 hours of mixing, damages to yeast cells were inspected by an electron microscope. Typical results are shown in **Fig.7** by photos. A yeast cell is broken and two cells have their surfaces cracked by the impeller



第７図　12時間撹拌された酵母菌の写真（5000倍）
Fig. 7　Yeast cell photos after 12 hour mixing (×5000)



第８図　撹拌による酵母スラリーの pH の変化
Fig. 8　Change in slurry pH by mixing.

shear of the pitched blade turbines. No damage is observed in the photo of yeast cells agitated by Fullzone.

Effects of shear stress on yeast can be evaluated by leakage of substance from yeast cells, i.e. comparing the rate of pH change or of protein concentration change in centrifuged supernatant of yeast slurry agitated by those impellers. **Fig.8** shows an example of these comparisons. The rate of pH change is decreased to a half by Fullzone as compared with the pitched blade turbines. The similar tendency was observed about the rate of protein concentration change. These results together with the shear rate distributions in **Fig.4** suggest that even Fullzone impellers might give the yeast cells some damage at the impeller tips unless impeller speed and mixing period are carefully restricted. This thought led to an idea that Fullzone should be modified to lower impeller speed and shorten mixing period, i.e. to lessen yeast cell damages, by larger impeller diameter such as shown in **Figs.1 and 3**. Added tests have shown that the rate of pH change can be still decreased by this modification.

Another test to quantify yeast cell damages in yeast tanks is dead cell count. The test results are shown in **Fig.9**, which compares the viable yeast cell percentage on the yeast slurry arrival to yeast tanks, with that after two days storage in yeast tanks. All the tanks used were equipped with Fullzone impellers, different from each other in diameter. The decrease in the yeast cell viability is negligibly small or not observed. The larger impeller tends to bring less decrease in the yeast cell viability. The tank YT-7, having its impeller diameter such as shown in **Fig.3** resulted in no decrease in the yeast cell viability.

3. 3 Cooling

Yeast tanks are cooled by a cooling medium flowing in jackets. **Fig.3** suggests that it might be difficult for the existing tank design to cool the yeast slurry uniformly. If the yeast slurry is stagnant by the tank wall cooling must be very slow at tank core although it might be faster near the jacket surface. There are no data available to confirm this suggestion. However, it was experienced that the temperature increase of the cooling medium between jacket inlet and outlet was so small in cooling operation by pitched blade turbines that moisture in the air was widely frozen on the outside surfaces of jacket. When Fullzone was tested, there was almost no frost on the jacket outside surfaces, i.e. jacket heat transfer became much faster. Some estimations show that heat transfer coefficient increases more than twice.

3. 4 Impeller power

Fullzone's impeller power is easily calculated from the torque data in **Fig.2**. It is as follows; 0.07kW at 5rpm, 0.14kW at 10rpm, and 0.37kW at 18rpm, for 5kL yeast slurry. The pitched blade turbines shown in **Fig.3** require 2.3kW at 60rpm for the same amount of yeast slurry.

3. 5 Sanitariness

The yeast tanks with Fullzone impellers were operated in an actual beer production process for 15 months. Meanwhile samples of yeast slurry were taken from the yeast charge lines to fermentation tanks and were inspected to confirm that there was no microbial contamination. The drain after CIP operations of the yeast tanks was also inspected periodically. No contamination was found. Thus, the new yeast tank design is verified to have enough sanitariness required for the beer production.

Conclusion

A new yeast tank design, modifying Fullzone as a low-shear impeller, was applied to an actual beer production process, and was found to be effective in the following improvements:

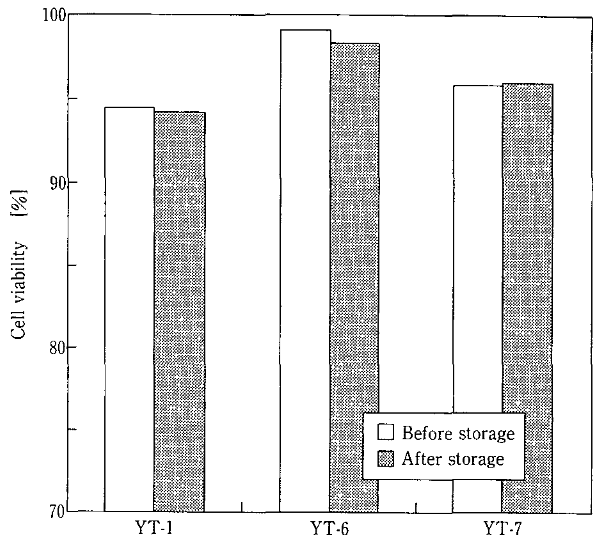
(1) Temperature distribution was more uniform in the new yeast tanks.

(2) No serious variation in the yeast cell concentration was detected of the slurry supplid from the new yeast tanks to fermentation tanks.

(3) Dead cell counts detected no increase in the new yeast tanks.

(4) Slurry cooling became faster and yeast temperature was more controllable.

(5) Impeller power was reduced to less than a quarter of the existing yeast tanks.



第９図　酵母タンクに２日間保存した時の菌体生存率の変化

Fig. 9　Yeast cell viability before and after 2-days storage.

Faster cooling or more uniform mixing requires higher speed of impeller rotation however, this can cause increase in yeast cell damages. When cooling is too slow, or storage temperature fluctuates too largely, the yeast degenerates. When yeast supply concentration fluctuates too largely, easy control of yeast charge amount is lost. There must be the best decision of impeller speed in cooling storage temperature control, and attaining uniformity of cell concentration in yeast slurry supply to fermentation tanks, so that the yeast can maintain its best fermentation ability and the beer fermentation becomes most controllable. It is reasonable to think that this decision will be influenced by the difference in biological properties of various species of yeast. Future works are expected to explain how the decision should be made.

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