Experimental set-up and methodology to study the oil/ammonia separation for combined absorption power and cooling systems

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Abstract:

The power and air conditioning energy needs in a facility can be satisfied by a combined power and cooling cycle driven by low grade heat. Operating this cycle to match the building demands improves the overall annual performance. A few authors have proposed to generate both shaft power and refrigeration by the hybridization of an absorption refrigeration cycle and a Rankine cycle using ammonia/water as working fluid. This paper proposes an experimental design set up and methodology to study the separation of oil from ammonia for application in combined power and cooling systems. The experimental procedure to calibrate an in situ coriolis flow and densitometer to measure real time oil concentration in a R717-naphthenic oil mixture has been presented.

Keywords:

Refrigerant-oil, Mixture, Separator, Oil concentration, Density

1. Introduction

It is possible to convert thermal energy into either power or cooling. Traditionally separate cycles are used to convert the heat either into power or cooling depending on the need. A heat supply can satisfy a cooling demand by utilizing an absorptive refrigeration cycle or a power demand by utilizing a Rankine cycle. Therefore, it is possible to combine the two cycles since they share a common energy form at the input. Interestingly, the two cycles could also share a working fluid when the organic Rankine cycle is considered. The resulting combined power and cooling cycle can be driven by low grade solar heat to service power and air conditioning demands in buildings. Since power and cooling requirements in buildings vary with seasons of the year; the output of the combined cycle can be adjusted accordingly. This feature ensures that the operation of the combined power and cooling cycle can always follow the demand thus improving the overall annual performance.

Reference [1] is accredited as one of the early proposers for a combined power and refrigeration cycle. To generate both shaft power and refrigeration, he suggested the coupling of an absorptive refrigeration cycle and a traditional Rankine cycle. Reference [2] proposed to combine absorption refrigeration and Kalina power cycles for the simultaneous production of power and cooling. They concluded that the combined cycle consumed less energy than that required to drive the parent cycles separately. Most of the literature available [3–5] covers only the theoretical aspect of the combined power and cooling cycles. Reference [6] presents an overview of the absorption cycles proposed in the literature for producing combined power and cooling. The various criteria used in the literature to evaluate their performance are presented and discussed. They point out that the main advantage of the configurations is that they enable low-grade heat such as solar energy or waste heat to be used.

Reference [7] constructed an experimental system to demonstrate the feasibility of the ammonia/water combined cycle; they simulated the expander with a throttle valve and heat exchanger, later Reference [8] modified an open drive scroll compressor to operate as an expander and introduced it to the system. In both cases, the potential for the cycle was evidenced but not concluded and further studies were suggested to realize the potential.

In their study of the experimental characterization and modelling of a scroll expander, Mendoza et al. [9] also modified a scroll compressor to work as an expander with air and ammonia as working fluids, and concluded that lubrication had a positive effect on the specific power produced by the expander. However the lubrication oil may have negative effects on the absorption and evaporation process when the lubricated scroll expander is employed in a power and cooling cycle such as the one shown in Figure 1. Figure 1 shows a proposed absorption power and cooling cycle with the capability of splitting the working fluid into two streams: the power generating stream and the cold producing stream. This feature enables the cycle to be operated as per the exact demand requirements however the however the oil introduced at the expander needs to be removed before joining the oil free cold producing stream.

This paper proposes an experimental design set up and methodology to study the separation of oil from ammonia. The study involves two stages; the first stage will recommends a viable oil concentration measurement method while the second stage proposes the procedure of investigating effectiveness of oil separators.

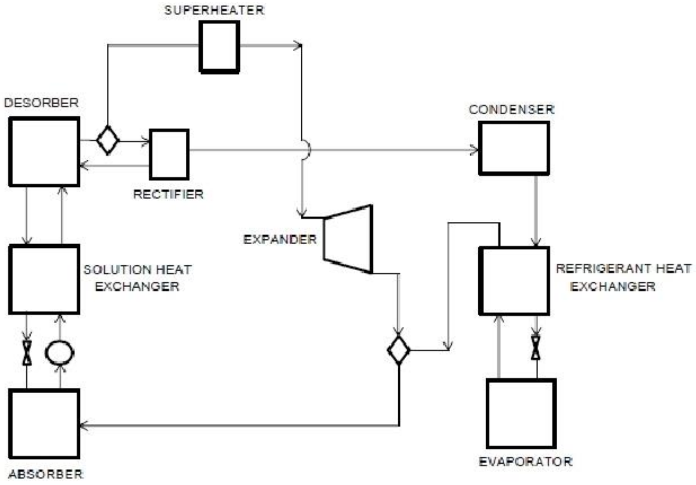


Fig. 1. Absorption power and cooling cycle.

2. Theoretical background

2.1. Lubricants

The key reason for oil in vapor compression refrigeration systems is for compressor lubrication and sealing. Lubricants miscible with refrigerants are preferred in vapor compression systems to avoid oil chocking and heat transfer deterioration in the evaporator since oil return to the compressor is guaranteed by the miscibility of the lubricant with the refrigerant. A refrigeration system charged with a refrigerant such as ammonia or carbon dioxide that are immiscible with lubricants requires an oil separator located at the discharge line of the compressor to recapture the oil and feed it back to the compressor [10]. Table 1 gives the suitability of different lubricants to some refrigerants. Since the working fluid in this study is ammonia, focus will be placed on mineral oil and

Polyalphaolefin lubrication types. Poly-alkalene-glycol type lubricants are suitable only in limited applications and will not be considered in this investigation.

Table 1. Suitability of lubricants for some refrigerants (X for good suitability; (X) for applicable with limitations) [11]

Lubricant type	Refrigerant type		
	Ammonia	Carbon dioxide	CFCs and HCFCs
Traditional Mineral Oil (MO)	X		X
Alkyl-benzine (AB)	(X)		X
MO + AB	(X)		X
Polyolester (POE)		(X)	(X)
Polyalphaolefin (PAO)	X		(X)
Poly-alkalene-glycol (PAG)	(X)	(X)	

Mineral oil lubricants are products of refining crude oil. There are three categories of mineral oil lubricants: paraffinic oils, naphthenic oils and aromatic oils. Paraffinic oils are manufactured either by hydrocracking or solvent extraction process while naphthenic oils are produced from crude oil distillates. Aromatic oils are products of refining process in manufacture of paraffinic oils. The chemical structure and properties polyalphaolefins (synthetic hydrocarbons) are identical to those of mineral oils. Polyalphaolefins are manufactured by polymerization of hydrocarbon molecules [12].

2.2. Separators

The working principle of most oil separators in the refrigeration industry involves either coalescence or centrifugation. Coalescence is a phenomenon in which two substances identical but separated tend to concentrate whereas centrifugation involves the use of centrifugal force to separate substances with different densities.

2.2.1 Coalescing oil separator

A coalescing oil separator comprises of filter element housed in a casing with three ports as shown in Figure 2. The refrigerant-oil mixture enters the separator at the inlet port A and then passes through the element from inside to outside. The inner layer of the element is finer that the outer layer. The fine filter material of the inner layer arrests fine oil droplets and forces them to collide and form larger oil droplets. The large oil droplets are then drained to the bottom of the separator through gravity. Port C provides an outlet for the collected oil while Port B is an outlet for the purified refrigerant.

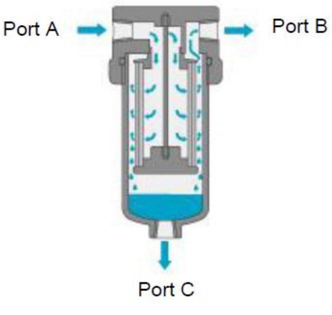


Fig. 2. Operation principle of a coalescing oil separator [13]

2.2.2 Centrifugal oil separator

Figure 3 shows a centrifugal oil separator. It consists of three ports and features a helical path. The refrigerant-oil mixture enters through port A and centrifugally flows along the helical path. The centrifugal force flings the oil particles to the inner walls of the casing which then flows down an oil collection cavity at the bottom of the separator. Port C provides an outlet for the collected oil while Port B is an outlet for the purified refrigerant.

Fig. 3. Centrifugal oil separator [14]

In their study of techniques to predict the performance of a cyclone oil separator, Murakami et al. [15] concluded that centrifugal separation improved in the high refrigerant-oil mixture flow rate because the centrifugal force that acted on the oil droplets increased. The effectiveness of an oil separator (ε_{sep}) can be expressed as:

$$\varepsilon_{sep} = \frac{M_{before\_sep} - M_{after\_sep}}{M_{before\_sep}} \tag{1}$$

2.3. Property based measurement

For some time now researchers have been taking advantage of the behavior of some thermosphysical properties of the refrigerant-oil mixture at varying oil concentrations to develop appropriate transducers to measure the oil concentration. Table 2 summarizes some of the property based oil concentration measurement methods. Density, light absorption, viscosity and acoustic velocity changes were monitored at varying oil concentrations and temperature and suitable correlations developed. The measurement error in all the cases was less than 0.05 with the light absorption and density based techniques registering the best accuracies.

Table 2. Some property based oil concentration measurement methods [16]

Property	Measurement	Accuracy	Refrigerant-oil
Density	Correlating the density of the refrigerant-oil mixture to temperature and oil concentration [17].	0.2 wt.%	R134a/POE
Light absorption	Correlating the amount of ultra-violet light absorbance in a liquid refrigerant-oil mixture sample to the oil concentration [18].	0.1 wt.%	R12/mineral oil; R134a/PAG
Viscosity	Correlating the viscosity of known refrigerant-oil mixture samples to temperature and oil concentration [19].	1-2 wt.%	R12 and R22 with naphthenic oil; R502/AB
Acoustic velocity	Correlating the acoustic velocity in the refrigerant-oil mixture to temperature and oil concentration [20].	5 wt.%	R22/AB

This study will involve modifying the test bench used by Mendoza et al. [9] at CREVER group of the Universitat Rovira i Virgili (Spain). The test bench is already equipped with a coriolis flow and density sensor, the density based measurement method was found appropriate for this study.

3. Experiments

A standard gravimetric method will be employed to check the accuracy of the density based oil concentration measurement method.

3.1. Gravimetric method

The ASHRAE standard 41.4-1996 [21] provides a guideline for determining the oil concentration in a refrigerant-oil mixture. This method involves first sampling of the refrigerant-oil mixture in its liquid phase then recording mass of the sample. Next the refrigerant component is boiled away and mass of the residue is noted. The standard demands the venting of at least three successive samples each with a mass of approximately 0.45 kg. The average of the three samples will be taken as the oil concentration of the refrigerant-oil mixture. From this procedure, the following relationship can be deduced:

$$Oil_{conc} = \frac{Mass_{oil}}{Mass_{oil} + Mass_{rfg}} \tag{2}$$

Reference [19] points out that in addition to being laborious, this method is useless when dynamic investigations are required and that the removal of the relatively large samples affects the operation of the system. Therefore for transient analysis in small systems, an in situ measuring method is more suitable.

3.2. Density based method

The saturation density of the refrigerant-oil mixture can be evaluated by assuming that both volume and mass are additive quantities for the mixture as stipulated by ASHRAE [21]. The additive volume assumption is usually disobeyed in refrigerant-oil mixtures therefore density measurements can be made with a density sensor and correlated with the oil concentration. The Jensen model [22] as highlighted in equations 3 and 4 utilizes density measurement to define the mixing ratio of refrigerant and refrigeration oil. To validate this model, the density of the refrigerant can be obtained from Engineering Equation Solver (EES) software [26] and the oil density can be obtained from data supplied by the manufacturer.

$$\rho_{mix} = \frac{\rho_{oil}}{1 + (1 - oil_{conc})(\rho_{oil} / \rho_{rfg} - 1)} \tag{3}$$

$$oil_{conc} = (\rho_{rfg} / \rho_{mix} - 1)[1 / (\rho_{rfg} / \rho_{oil} - 1)] \tag{4}$$

In addition to temperature and oil concentration, the effects of liquid compressibility to the density of the refrigerant-oil mixture will also be examined as suggested by Bayani et al. [17]. This will entail the inclusion of the effect of pressure into the experiment. The studied mixture will be adequately subcooled to ensure that only a completely liquid (zero void fraction) mixture is sampled.

Reference [23] studied on an online measurement method to determine the oil discharge ratio by utilizing Coriolis mass flow meter in a calorimeter. They also conducted the gravimetric method and the light absorption method for comparison; they concluded that the density method has a similar level accuracy and precision compared with standard sampling method, and have more accuracy and precision than light absorption method.

4. Experimental setup and procedure

4.1. Calibration for oil concentration measurement

The experiments were conducted using as slightly modified version of the CREVER group's scroll expander characterization test bench described by Mendoza et al. [9]. Figure 4 shows the oil concentration calibration test bench.The subcooler controls the temperature while the pump regulates the pressure and mass flow rate of the working fluid. Three outputs are provided by the coriolis meter: temperature, mass flow rate and density. The test bench is furnished with a sampling port for carrying out the gravimetric method. Table 3 highlights the accuracies of the measurement transducers in the test bench.

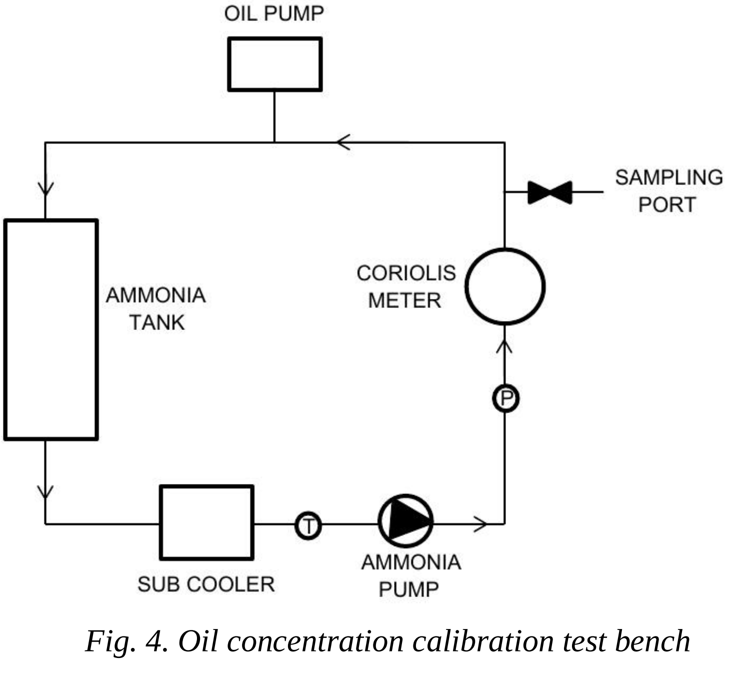


Fig. 4. Oil concentration calibration test bench

Table 3. Measurement accuracies of the transducers in the test bench [9]

Instrument	Variable	Accuracy
Baumer mod. E913	Pressure	±5 kPa
PT 100 Aplytex 4 wires	Temperature	±0.3 K
Micro motion CFS015	Mass flow rate	±0.05% of rate
	Density	±0.2 kg/m^3
	Temperature	±1 K

The gravimetric method is only valid for a refrigerant-oil mixture in liquid state as instructed by ASHRAE [22]. Therefore the subcooler will be set at 5K below the saturation temperature to ensure that the sampled mixture is completely liquid.

Reference [17] notes that over the temperature range of industrial interest, the density differences between refrigerants and their lubricating oils are about 200-400 kg/m^3. Thus for the selected coriolis meter an oil concentration accuracy of ±0.1 wt. % oil is expected: $(\pm 0.2/200) \times 100 = \pm 0.1\%$. This level of accuracy is sufficient because a study [19] utilizing an inferior density sensor (±2.0 kg/m^3 accuracy) produced satisfactory results.

Polyalphaolefin (PAO) lubricants provide good extended life stability, maintain viscosity at high temperatures while still flow freely at low temperatures. However when used without additives, PAOs can result in shrinkage of O-rings and other elastomers [25]. To avoid the introduction of unwanted dynamics in the experiment, polyaphaolefin lubrication will not be used in this study. Therefore in this study, a mineral type lubricant will be utilized. Suniso 4GS (a naphthenic mineral oil) was selected for this investigation. Salient properties of the selected mineral oil are shown in Table 4.

Table 4. Property data for Suniso 4GS mineral oil [24]

Property / Condition	Value	Unit
Density / 15^{o}C	915	kg/m^3
Viscosity / 40^{o}C	54.90	mm^2/s
Viscosity / 100^{o}C	5.97	mm^2/s

To operate the test bench, first the system is evacuated then charged with a known amount of ammonia. The temperature and pressure of the ammonia is varied by manipulating the subcooler and pump conditions respectively. Effects of the varying temperature and pressure on the density of the ammonia are noted. The expansion tank can be used as a reservoir to cope with the frequent venting required by the ASHRAE standard test.

Next, a predetermined amount of lubricating oil is added to the ammonia through the oil supply. The oil supply system comprises of a BT4a solenoid dosing pump from prominent® and an oil reservoir. The feed rate of the pump can be controlled by adjusting the stroke length and stroking rate. The pump can withstand a maximum back pressure of 16 bars. The quantity of oil discharged from the pump is considered to be the same as the oil circulation quantity of the oil/refrigerant mixture circulating in the test bench since under steady conditions of operation, the oil retention at each individual system component could be constant for a fixed system Yan et al. [23].

The oil concentration (Oil_{conc}) is varied from 1 to 10%. For each oil concentration, the temperature and pressure of the ammonia-oil mixture are varied and density measurements are taken. The collected data is then used to formulate a correlation to be used for the in situ real time density based oil concentration measurement for R717-naphthenic oil mixtures.

The gravimetric measurement method is carried out at each experimental state point to provide data which will be used to check the accuracy and eventual suitability of the density based method.

4.2. Effectiveness of separator(s)

The second phase of the study involves the determination of the effectiveness of the oil separation process. Figure 5 depicts how the scroll expander characterization test bench has been modified into an oil separator effectiveness test bench. Figure 5 shows a picture of the experimental set up and the scroll expander.

Separator 1 is a coalescing type and separator 2 is centrifugal type. Separator 1 will be studied first after which a working combination of the two will be investigated. Initially the system is evacuated then charged with ammonia. The speed of the scroll expander will determine the ammonia flow rate through the system. In this set up the expander speed is externally controlled by the operator. The knowledge of the ammonia flow rate informs the operator on the oil pump settings which depend on the oil concentration desired. Oil concentrations between 1 and 10% will be studied. The coriolis meter is located downstream of the separator assembly therefore the oil concentration value deduced from the density is an indication of the separator effectiveness. Effects of temperature, pressure and flow rate on the separator effectiveness will also be investigated.

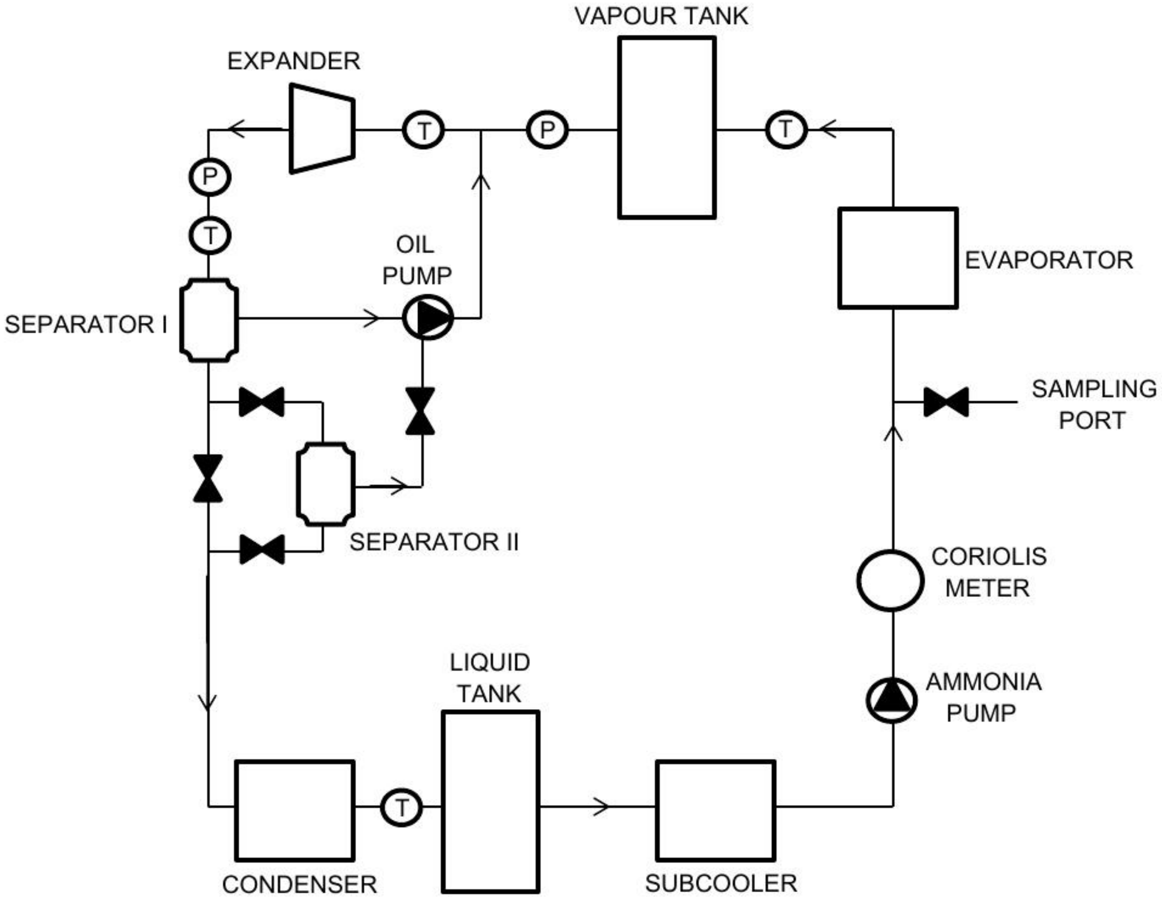
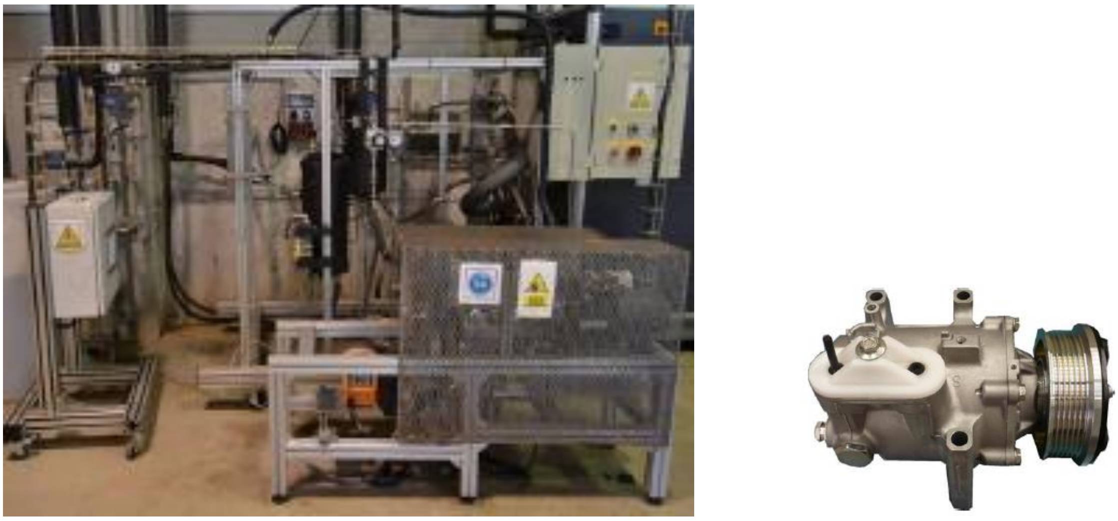


Fig. 5. Oil separator effectiveness test bench



(a) (b)

Fig.6. Oil separator effective test bench (a) and the scroll expander (b)

5. Conclusion

The experimental procedure to test an experimental set-up for the online measurement of oil concentration has been designed and built. The setup will provide a better platform for optimization criteria and design procedures intended for combined absorption power and cooling cycles. The set-up is also able to test the efficiency of oil separators.

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CFCs	Chlorofluorocarbons
HCFCs	Hydrochlorofluorocarbons
M	Mass
wt.	Weight

Subscripts

after_sep	After separator
before_sep	Before separator
conc	Concentration

mix	Mixture
oil	Oil
rfg	Refrigerant
sep	Separator

Greek Symbols

ε	Effectiveness	[-]
ρ	Density	[kg/m^3]

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