# WHITE PAPER ON

APPLICATION OF HYDRODYNAMIC CAVITATION FOR QUALITY ENHANCEMENT OF ALCOHOLIC BEVERAGES

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#### INTRODUCTION

The manufacturing process for alcoholic beverages comprise of primary fermentation. distillation followed by aging. Common substrates used for fermentation include grains , potatoes. sugar beats. grapes. cassava and agave. Typically. grape juice consists of 79% water, 20% carbohydrates and 1% organic acids. and trace amounts of phenolics, vitamins, minerals and nitrogenous compounds. Sugars , organic acids and phenolics contribute to the flavour of grape juice, while vitamins. minerals and nitrogenous compounds play important role in yeast growth and fermentation. Typical alcohol content of wines prepared from fermentation of grape juice or grains is typically in the range of 8 - 13 % . During fermentation, other substances are also produced known as congeners, which are other alcohols such as methanol , propyl alcohol, isobutyl alcohol and isoamyl/active amyl alcohol , acetaldehyde and some other higher aldehyde s, acetone and tannins. Although some congeners contribute to taste and aroma of alcoholic beverages, most of these substances are responsible for symptoms of hangover. Vod ka, which is a blend of rectified spirit and demineralized water in prescribed proportions. has alcohol content of~ 40 vol%. The main

organic acids that appear in grape juice are maleic acid, tai1aric acid and citric acid. These

.. acids give grape juice and wine their acidity and act as buffer to maintain wine pH at ~ 3.

They also play important role in balance of flavors. The tetm " phenolics" refers to large group of compounds containing at least one " phenol" moiety. i.e. at least one hydroxylated benzene ring. The composition of wine is complex and changes continuously during aging. Phenolic compounds play important role in determining quality of wine. Phenolics also act as antioxidants with mechanisms involving both metal chelation and free radical scaveng ing. Among phenolics, anthocyanins, non-anthocyanic phenols (including flavan-3-ols, fl avonols , and hydroxycinnamic acids) together with polymeric pigments resulting from the reaction between anthocyanins and other phenols ai·e the main compounds with high sensory influence

on wine. Anthocyanins and polymeric pigments are respons ible for color of red wine. while non-antho cya nic pheno ls (flavan-3-ol or flavonol) give wine their astringenc y. structure and bitterness. The antio xidant properties are mainly due to flavonols and stilbenes. Some volatile compounds related to aroma also have significant impact on wine quality. Wine aging can also modif y other compounds formed during fermentation such as higher alcohols, aldehydes , esters, acids and ketones. For wines aged in wooden barrels. a se ries of aromatic substance s also get transferred from wood to the wine. The volatile compo unds that get extracted from oak wood to wine mainly include furfural compounds, guaiacol. oak/whisky lactone. engenol. syring aldehyde and volatile phenol.

#### CHEMISTRY OF AGING OF ALCOHOLIC BEVERAGES

The chemistry of natural aging of wine is very complicated and has been a matter of investigatio n for past severa l decades. In one of the earliest st udies published in 1939, Nelson and Wheeler have reviewed and reported chemical changes accompanying natural aging of wines. These changes are mainly in terms of red uct io n in tartaric acid. color and tannin content and increase in volatile ester content. Decrease in alcohol content and increa se in acetaldehyde content was also reported. The precipitation of lees also caused reduction in tartaric ac id and tannin conten t. The literature on chemical mechanis m of aging of different types of wines is voluminous and no attempt is made here to present a comprehensive review of this literature . However, we summarize herewith results of some representative studies addressing chemistry of wine aging.

I. Wildenradt and Singleton (197 4) have reported that oxidatio n of ethanol to acetaldehyde by direct chemical reaction with air occurs at an appreciable rate in wine only by a coupled autooxidation of certain phenolic substanc es occurring in wine . The oxidation of

vicina l di- and trihydroxyphenols(e.g. catechins) in 12 vol% ethanol produced acetaldehyde. Wildenradt and Singleton (197 4) ha ve postulated a general mechani sm for autooxidation of phenols, ascorbic ac ids, melanoidin s. onediols and relat e d co mpound s. According to this mec hani sm, ox idatio n of phenol to quinon e resu lts in production of stro ng oxidant (H2O ). which oxidizes ethanol to acetaldehyde.

1. Timberlake and Bridle (19 76) have studi ed inte ractions between pure anthocyanins. phenolic compounds and acetaldehyde in tartarate buffer. Several reactions occurred simultaneou sly. Reactio ns between anthocyanins and phenolic compounds were slow, resulting in fo1mation of xanthylium salt. Reac tion between anthoc yanin and Mv-3- glucoside resulted in slo w polymerization. Linking of phenolics and anthocyanins by CH3-C H- bridges lead to formatio n of highl y colored new compounds.
2. Mateus and de Freitas (2001) have st udied evo luti on and stabilit y of anthoc yanin derived pigments during wine aging. The degradation reaction of all pigments followed l'a order kinetics. The degradation rate constant s of anthocyanin -p yruvic acid adduc t was lower than anthocyanin mo noglucos ides . The leve ls of Mv-3-g lucos ide-pyruvic aci d adduct and its acylated form started to decrease after around l 00 days of wine fortification.
3. Fulcrand et al. (2006) have investigated mechanism s of phenolic reactions during wine making and aging. Fulcrand et al. (2006) have postulated that reactivity of phenolics is due to position of - OH group on aromatic nuc le i. Ortho -OH group promotes oxidation. while meta - OH group ind uces elect rophilic aromatic subs titutio n. Both types of hydroxylatio ns occur in flavono id structure on se parate rings. Flavo no ids can also undergo nucleophilic addition on central aromatic ring. The aromatic ring of flavo no id can undergo polyco nden satio n reacti on mediated by an aldehyde. The products are anthocyanins/flavanol polymers/ copolymers cons titutin g both. Flava nol polymer s

rearrange into vinyl flavano ls and xanthylium pigments. Vinyl flavanols can react with positively charged ring of anthocyanins to yield pyranoanthocyanins.

1. Brouillard and Dangle s ( 1994) have reviewed molecular interaction s among anthocyanin and their role in formation of new pigments during wine aging. Common storage conditions employed during aging of red wine (long contact period, contact with wood. low pH, low temperature and acidic environme nt) have favorable effect on molecular associations between wine anthocyanins and aromatic planar colorless molecules in the medium. The factors which affected anthocyanin non-covalent interactions were: (1) pigment and copigment concentration and structure s. (2) pH. (3) type of solvent, and (4) temperature. Brouillard and Dangles have hypothe s ized that complex of a pigment with one of its copigments could be the starting point of covalent linkages between molecules.
2. The hydrogen bonding struct ure of water-ethanol in alcoholic beverages like whisky and vodka has significant impact on the aroma and mouth-feel. Nose et al. (2017) have reported effects of other solutes on interactio n between water and ethanol in aged whisky. The phenolic acids and aldehydes were found to have influence structure making effect regardless of presence/absence of acetic acid. The amount of total phenolics in whisky were a function of type of cask used. The effect of extractio n of phenolics was the highest for sherry and new casks, while used/c harred casks yielded lesse r quantity of phenolics for same aging time. Measurement of -OH proton chemical shifts of whiskies matured in casks of different kinds as a function of concentration of different phenols indica ted that change of hydrogen bonding structure of whisky (aged in wood casks) was due to direct effect of chemical components from casks - mainly acidic components , aldehydes such as vanillein and acidic compounds. Oxidation processes of several compounds in whisky are regarded to be important reactions for whisky maturation. Some aldehydes in whisky are oxidized into acids during maturation. The chemical shift values ( 8) increa sed much

with oxidation of aldehydes to acids. The hydrogen bonding structure of whisky is strengthened through oxidatio n reactions during maturation. Lactones contribute to flavor characteristics of whisky. Some of them are derived from wood components of cask, while some are produced during fermentation by bacteria (Brewer' s yeast and lactic acid bacteria). Pantolactone and octano lacto ne promote the proton exchange between water and ethanol causing higher chemical shift. Sugar components also increased in whisky during aging in cask. However. glucose in such high concentration had come mainly from she rry components soaked in oak wood. However, glucose was not found to influence the hydrogen bonding struct ure of wate r-ethanol system. Esters such as ethyl caproate, ethyl caprylate , isoa myl/ethyl acetate also did not ca use any OH-proton shift. Thus, the compo und s coming from cask (acids , pol yphenols, aldehyde s) strengthened the hydrogen bonding structure of water-ethanol in whisky.

1. Hu et al. (20 I0) have assessed the hydrogen bonding prevalent in both vodka and water­ ethanol so lut ion using 1H NMR. FTIR and Raman spectroscopy. The analysis revealed existence of water-rich hyd rates of compositio n eth anol:(5.3 ) H20 in both vodka and water-ethanol solutions. Thi s composition was close to that of clathrate-hydrate observed at low temperature. which implies a cage-like morphology. Hu et al. (2010) have defined the "structu rabilit y parameter" defined by the concentratio n of ethanol:5 .3 H20 hydrate as

compared to pure ethanol-wate r mixture at same ethanol co ncentration. The structurabi lity parameter is essentia lly the measure of deviation of vodka from pure water-ethanol solution. The vodka drinkers develop brand preference on the basis of ethano l.H20 structure. Beverages with lo w structu rability are likely to be perceived as " watery" . Beverages with high structurabilit y harbor trans ient cage like entities where ethanol molecule is sequestrated surrounding water molec ules. At high alcohol content (> 19 mol% or> 44 vol%), clusters of alco hol molecules appear and these clusters stimulat e

the palate differently from either water or ethanol:5.3H20 cage structure. Hu et al. (20 IO) have also pondered over causes leading to differences in structurability of vodka. One possible cause is pre se nce of trace compounds influencing H-bonding and thus alter component distrib ut ion. Another conclusion of study of Hu et al. (20 IO) is that clathrate structure of ethanol:5.3 H20 is trans ie nt in nature. Moreover, composition of this structure s significant at ethanol composition of 40 vol%, which is slightly below the composition where pure ethanol clusters form.

#### USE OF ULTRASOUND WAVES FOR AGING OF WINES

Application of ultraso nic waves for artificial aging of fermented and distilled alcoholic liquors was first reported by Bachman and Wilkins (1937) in a US patent. The process was carried out in an oak container and in presence of air. Application of ultrasound waves accelerated the oxidation and esterification reactions. The oxidation process essentially comprises of conversion of alcohol to aldehyde and further to acid. Two other patents that were iss ued in the area of artificial wine aging with sonicatio n were: (1) Dudar et al. (1980) - in which a process for acceleration of ripening of spirits was described in presence of wood sto ves that serve as a so urce of bouquet improving components from additives such as wood. Chang and Chen (2002) have reported accelerated aging of wines using 20 kHz ult rasound. Two kinds of wines. one made from rice and another from maize. were subjected to so nication followed by atomization through IO mm orifice. Wine emerged in the form of mist and mist particle s were collected for analysis. No sig nificant changes in pH values of both wines were detected after sonicatio n tre atm ent. The alcohol contents of the two wines also showed minor reduction with sonicatio n. Rice wines showed sharp reduction in aceta ldeh yde with sonication (from I 05 mg/L in fresh wine to 70 mg/L after 16 ultrasonic treatment

cycles) . The polyols co ntent (viz. methanol, 1- propanol. 2.3-dimethyl butanol and 2-methyl 1-p ropanol) of rice wines also showed signifi ca nt red uctio n with ultr aso nic treatment . On the other hand. maize wines did not sho w any reduct ion of acetaldehyde content after 16 ultrasonic tre at ments. Co ntents of some polyols such as 1- p ropanol. 2.3-dim ethyl butano l. and 2-m e thyl 1-p ropano l s howed slight increase with ult rasonic trea tment. Surprisin gly, the ethyl ace tate co ntent showed shar p reduc tio n af te r ult rasonic treatme nt (fro m **114** mg/L in fresh wine to 61 mg/L post treat ment). Thi s esse ntially mea nt that ex posure to 20 kHz sonication was potentially good method for acce lera tion of agin g of rice win es, but not maize wines. In an o ther in vestigation, C hang (2004) has inves tigated eff ec t of high freq uency (1.6 MHz) sonication and y-irradiation o n ag ing of maize wine s. It was revea le d that high freq uency sonication was no t effec tive in altering taste of maize wines. This trea tment resulte d in red uction in alco hol a nd ester co ntent of wine with rise in aceta ld e hyde and polyol content. The y-radiation trea tment, however, had the des irable effec t of reduction in polyol conte nt of wine with es ter and alco hol cont ents of wine rema ined unchanged. Thus, y­ radiation treatment was potential alternative for acce leration of aging of mai ze wines.

In another investigatio n, Chang (2005 ) studied influence of sonication treatments for acce leratio n of aging process in rice a lcoholic beverage s. Ultrasound waves of two different freq uencies, viz. 20 kHz and 1.6 MHz were employed and the results were co mpared again st properties attained by wine age d in fired clay containers fo r I year. Ultr aso und treatme nts fo r both freque nc ies were able to red uce quantity of acetald e hyde and co nge ners such as methanol, 1-propanol, 2, 3- dimethyl but anol, and 2-me thyl 1-propano l, in concurr e nce with rise in ester conte nt. The taste of wine trea ted with 1 .6 MHz ultrasound was not as good as the one trea ted at 20 kHz. Moreover, tas te of wine trea ted at 1.6 MHz reduced progressively as the number of treat ments increased. On the other hand, rice alco holic beve rages treated 16 ti mes with 20 kHz ultrasound had taste eq uivalent to con ventio nal o ne year aged rice

alcoholic beverage. Chang (2005) has emphasized on optimization of power of ultrasound waves for aging of alcoholic beve rages.

#### EFFECT OF HIGH PRESSURE TREATMENT ON AGING CHARACTERISTICS OF WINES

Tao et al. (20 l2) have stud ied the effect of high press ure treatment on the physicoc hemica l and sensorial prope1ties of red wine. High pressure treatment had signi ficant influence on chromati c characteristics and phenolics content/composition of wine after treatment at 650 MPa for 0.25, 0.5, l and 2h. 2 h HP treatment , however. signific antly reduced the intensitie s of sour and fruity odor of wine. Tabilo-Munizaga et al. (20 l4 ) have reported that hig h pressure treatm ent of white wine (Sau vignon blanc) at 450 MPa (for 3 or 5 min) modified the a-helical and P-sheet struct ure of wine proteins, and imp roved their thermal stability during storage. Zhu et al. (2016 ) ha ve reported effect of high pressure treatme nt on aging characteristics of Chinese wines. The samples were treated at press ure of 300 and 400 MPa for 15 and 30 min , and changes in the properties were co mpared with wine aged for 6 years with conventional techniques. Th e results of Zhu et al. (2016 ) can be summarized as follows:

*Total acid content:* High press ure treatment contributed to lowering of total acid content. **HP** treatment at 400 MPa for 30 min yielded the lowest value of 7.7 % total acid content. while a decline of 14.1% was observed in 6 year aged liquor. This reduction in acidity may have bee n caused by the loss of volatile acids and alcohol components during HP treatment, and hence, considered as indicator of aging of liq uors. S imilar result s have been reported by Pareira et al. for Malaysian wines and Pisarnits kii. O verall d iffere nces between the four HP treated

sample s were not significa nt when they were considered together. However, d ifference s existed between 300 and 400 MPa treated samples (d uration 15 /3 0 min) indicating that

pressure level could be more effective factor than holding (or treatment ) time in infl uen cing ac id composition of wines.

*Alcohol content:* A slight decl ine in the alcohol content was observed in comparison with young liquor without high press ure treatment - with the lowest alcohol content obtained following HP treatment at 400 MPa for 30 min . Alcohol content of conventionally aged samples was. howeve r, lower than all HP treated samples. It is recog nized that there will be some decline in the alcohol content during natural aging process of liquors. Through long time maturation, the odour peculia r to ethanol is reduced. and as a consequence, the tastes are altered to be favourable after aging. These have been linked to the changes in structure of water and ethanol molec ules. Nose et al. linked the hydrogen bonding structure of water­ ethanol in aged whisky to I H NMR chemical shifts of OH of water and ethanol. Furusawa et al. (1990) also reported that some volatile and non-vo latile co mpounds could assist the formation ethanol-water clus ters during aging - which leads to ethanol stim ulation. Typical composition of wine is l g/L aroma compounds, ethanol I 00 g/L and water 900 g/L.

*Total ester content:* Total ester contents of high pressure treated wine samples were signi ficantly higher, which is a feature also seen in samples of natura lly aged wines. Total ester content of samples treated at 300 - 400 MPa was in the range of 0.95 - 1.02 g/L, which is - 5% higher than young wine. Total ester content of 6 year aged wine was - 2 g/L. which is twice the amount present in HP treated wine. Esters could be most important class of all aroma constitutes in wine. More than 30 kind s of esters have been found in so me commercial brands. Es ters are products of esterification reaction between acids and alcohols during the process of fermentation and aging. especially the ethyl esters. which could be a reaso n for reduction in total acid and alcohol contents during aging. The enhancing effect of pressure on esterification reactions has been explained by the princ iple of Le Chatelier which states that any phenomenon accompanied by a dec rease in reac tion volume is enhanced by an increase



in press ure. As a res ult. high press ure trea tm e nt favors the incr eas ing levels of total este r co ntents in wine.

*Total solids content:* The total res id ual so lid content represe nts the non-vola tile substance and/o r vola til e s ubstances of high boiling point. Solid conte nt is undesirable inde x in co mme rcial liq uors, and lo w solid co ntent is desired for high quality wines. Interac tions between organic acid and metal ions during manu facturing process are the main cause of solids . Metal ions - mainly calcium and sodiu m - accumulate in wine aged for several years. The source of this is the materia l of constructio n of contai ner. Another possible so urce of high solids content is generatio n of esters of high boiling point following high pressure trea tment. The most commo n es ters detected in wines are ethyl acetate, ethyl buty rate. ethyl hexanoa te, eth yl lactate, ethyl oenanthate. and ethyl palmitat e. The last two esters were detected in naturall y aged wines but not in high press ure trea ted wines.

#### USE OF HYDRODYNAMIC CAVITATION FOR ACCELERATED AGING OF ALCOHOLIC BEVERAGES

The US patent no. 9,474 ,30 IB2 (Oc tober 25, 2016) by Cavitation Techno logies Inc., Chatsworth. CA. USA, has disclosed a process for rapid modification of beverage fl uid s by flow through different cavita tio n de vices. The cav itati on device invented by Gordon et al. has a cylindri cal metal body with an inlet and outlet tube. The inlet cone is located in front of multi-jet nozzle along flow path. Another guide co ne featuring spiral guides over it is positioned behind the nozzles. The multi-jet no zzle is e sse nti all y a metal disk with four channels havi ng abrupt co ntraction and expansion. This section is followed by a working chamber compri sing a guide.co ne and convergent co ne. Outlet from convergent cone leads to a vortex chamber or generator compris in g of disks with curved flow guides that are coax ially

aligned. These flow guid es esse ntiall y generate multiple curved flow paths with rapid and abrupt change in flow area. This generates rapid pressure variation in the flow. which is man ifested in the form of trans ie nt cav itat ion. Cavi tation is ge neration, g rowth and impl os ive collapse of tin y gas or vapor bubble s . The se bubbles may already exist in the liquid or the y are generated in the flow at locations of fast co ntractio n/expans ion of flow. where bulk pressure in the liquid falls very low - close to vapor pressure of liquid at bulk temperature. After their ince ption. the bubbles undergo volum e oscillations due to fluctuations in bulk pressure. Rapid co ntraction and expansion of flow generates large turbulent press ure fluctuations in the bulk pressure due to the pressure head loss . In such situatio n, the cavitatio n bubbl e may undergo initial expansion due to these fluctuations to several times its original size. This is accompanied by large evapo ration of vapor in the bubble , which diffuses towards core of the bubble. As the bubble undergoes rapid contraction with reco very of bulk pressure, the vapor in the bubble d iff uses back to the bubble interface and undergoe s condensation. However, in the final moment s of transient bubble colla pse, the bubbl e interface (or bubble wall) recedes at extremely high velocity due to which not all of the vapor molecules that have entered the bubble durin g expansio n can escape. The temp erature and pressure in the bubble reaches extreme , as the bubble is co mpressed adiabat ically to very small volumes. The vapor molecules "entrapped " in the bubble undergo thermal dissoc iation at ex treme conditi ons generated in the bubble. This result s in formation of large number of che mica l spec ies, some of which are radica l species with high oxidatio n potential (such as ·oH or o· or *Ho; ).* The dominant radical species is the hyd roxyl or 'OH. which initiates hydroxylation and oxidatio n of the compo unds present in the bulk liquid. As the bubble ge ts fr ag mented at the point of minimum radius (o r maximum co mpression) during radial motio n, these chemica l species are released into the bulk liquid mediu m. where they ind uce num e rous che mical react ions. High pressure flow through cav itatio n de vice in vented by Gordon et al. also generates vigoro us

mixing of the bulk flow. In the context of maturation and aging of wines. both che mical effect of radical production and physical effect of intense mixing/homogenization of liquid have hig h relevance. Both of these effec ts lead to acceleration of reaction assoc iated with aging of wines. as stated in previous sections.

In order to support this claim. we present herewit h simula ti o ns of radial motion of cavitation bubbles using diffusion limited model that takes into account heat transfe r and vapo r trans port across bubble wall during radial motio n. The simula tions have been car ried out fo r flow throug h co nstrict io ns **48** as shown in Figs. 5 and 6 of the patent. This esse ntially is a co nverging - diverging nozz le **40** with accompanying spiral flow guides **44.** as shown in Fig. 3 of the patent. The bubble dynamics simulations show generation of strong mic roturbul ence and high intensity shock waves during the transient bubble motion in cav itati ng flow through nozzles like **48.** Th e bubble dynamics simulations also revea l pea k te mperature and press ure co nditions reached in the bubble during transient collapse. The exact dimensions of nozzle **48** are dec ided b y the capacity of overall unit (and may change with capacity), and hence, the present simulatio ns have been carried out using representative dimens io ns and process parameters, which are similar to those in actual unit. The flow geometry co nsidered in the simulations is an orifice sectio n. T he inl e t sect io n of the nozz le has diameter of 2 in.. while the throat sect io n has dia. of I in. Two air bubbles of initial radii 50 and I 00 microns have been co ns idered for simulations with pump discharge press ure of

500 psi. For operation at cavitation number = I, which is a the oretica l yar d s ti c k for initiation of cavita tio n. Figs. 1 and 2 indeed show extreme energy conce ntration ins ide the cav itation bubble, as the te mperat ure in side the bubble reac hes ~ 4000 **K** during transient co llapse. Ho wever, prior to transient co llapse, both bubbles of initia l s ize 50 a nd 100 microns undergo expansion to 7 to IO tim es their original size. This expan sio n is acco mpanied by evaporation of the solvent vapor in the bubble . The bulk liquid in present situatio n (vodka) has about ~

40 % alcohol and rest water. The major congeners pre se nt in vodka are 2-methyl 1-propanol (or isobutanol) = 73 ppm. acetaldehyde = 19 ppm and methanol= 10 ppm. The content of non-volatile matter in the original vodka (which are essentially large molec ular weight organic species such as paraffinic hydrocarbons or fatty acid esters) is also high. i.e. - 5.59 g/L. The hydrodynamic cavitatio n treat ment causes drastic reduc tion in levels of all congeners. The concentratio ns of 2-methyl 1-propanol and acetaldehyde are reduced to negligible leve ls. Most nota bly, the non-vo latile matter content of vodka is drastically red uced to ju st 3 to 5 mg/L. T hese res ults are essentially manifestatio ns of the physical and chemical effects produced by hyd rod ynamic cav itatio n. The mechanism of degradation of the co ngeners , ho we ver, can be different depending on their physical properties. Acetaldehyde has very high vapor pressure of 740 mm Hg at 20°C (ambient cond itio ns). Therefore, it is likel y to evaporate preferentially into the cavitation bubble during its expan sion and undergo thermal dissoc iatio n during transient collapse of the bubble. 2 -m ethyl 1-propanol (or isobutanol ) has vapor pressure of 9 mm Hg at 20°C. Due to suc h low vapor pressure and also small bulk conce ntration, the paitial pressure of 2-methyl 1-p ropanol at the bubble interface

is very low. Thus. it is unlike ly to evaporate into the cav itatio n bubble during expansion.

.. However, it is li kely that it und ergoes oxidation to isobutyraldehyde due to the oxidative radicals produced by the cavitation bubbles. Isobutyrald e hyde has hig h vapor pressure ( 18.23

kPa) and can undergo degradatio n through thermal dissoc iatio n in cavitation bubble s. The non- volatile matter is likely to und ergo physical degradation due to intense acoustic waves generated by the bubbles. This process is si milar in mechanis m to degradation of polymers under ultraso und treatment. The radica ls produced by the transient cavitation bubbles may assist this degradation. During transient bubble collapse. as the bubble core gets heated to extre mely high temperature, so me finite heat diffusio n through the bubble wall does occur. due to which the liquid in close vic init y of bubble inte1face gets heated to moderate

temperature (~ 500°C). The non- volat ile matter in vodka prese nt in interfac ial reg io n of cavitation bubble may undergo thermal degradation at these co nditio ns. Other congeners such as ketones and some light esters can also get degraded through thermal dissoc iatio n in cavitation bubble and/or hydroxylat ion/oxid atio n clue to the radicals produced by trans ient cavitation bubbles . Trans ient co llapse of cavitation bubble also produces moderately high temperature and press ure s in the bulk liquid in immediate vicinity of bubble interface. This may lead to protonation of water, whic h catalyzes esterifi catio n reaction between fatty acids and ethanol. Formation of ethyl esters of fatty acids not only improves sweetness of the alco hol ic beverages but also enhances odor and aroma. Phenolics , if present in original ethanol. ma y also undergo various reactio ns ind uce d by chemical species generated by trans ie nt cavitat ion. Elimination of congeners from vodka during hydrodynamic cavitation treatment causes remarkable improvement in its quality with no hangove r.

**CONCLUSION**

T his white paper has trie d to identify links betwee n chemistry of maturation/aging of

.. alcoholic beverages (like vodka and wines) and physical/chemical effects of hydrodynamic cavitation device inve nted by Gordon et al. (2016). The chemical effect produced by transient

ca vitation occurring in this device. i.e. generation of oxida tive radical species through thermal dissoc iatio n of volatile compounds at extreme conditions generated in side cavitation bubbles, see ms to have beneficial infl ue nce on vodka/wine cha racteris tics. This is in terms of eliminati on of all co ngeners such as aceta lcle h yde and isobutano l. The radicals generated by cavitation bubbles also help in oxidative degradation of non-vo latile organic matter in the beverage - assisted by the high press ure acoustic waves and int ense mic roturbulence produced by transient cav itatio n. The cav itati on device invented by Gordon et al. also

generates intense mixing and homoge nizatio n of flow due to sudden contraction/expansion and high-speed swirling generated in the flow. This inten se mixing also helps in effective degradation of non-volatile matter in the beverage. The moderately high temperature and pressure generated by transient cav itatio n at bubble interface also augments esterification reactions between organic acids (especially high molecular weight acids) and ethyl alcohol. Formation of esters imparts additional odor/aroma to the beve rage. while elimination of congeners reduces hangover. The analysis given in this white paper essentially gives physical and mechanistic explanation to the efficacy of hydrodynamic cavitation device inve nted by Gordon et al. (2016) in producing high quality alcoholic beverages.

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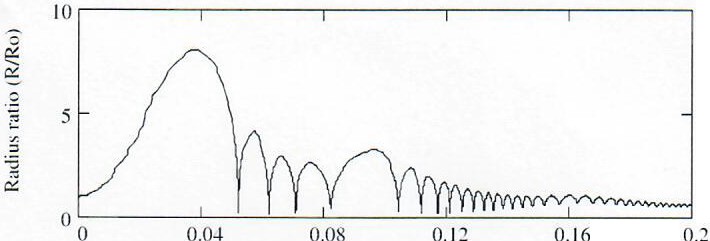
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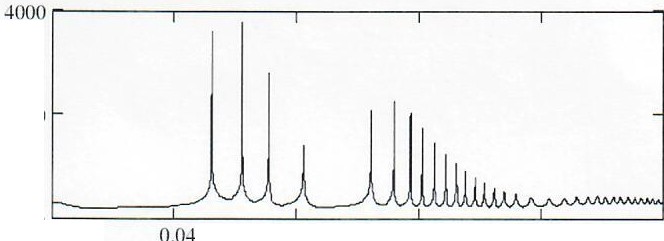
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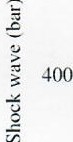
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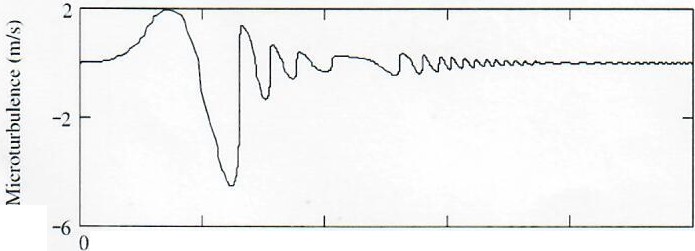
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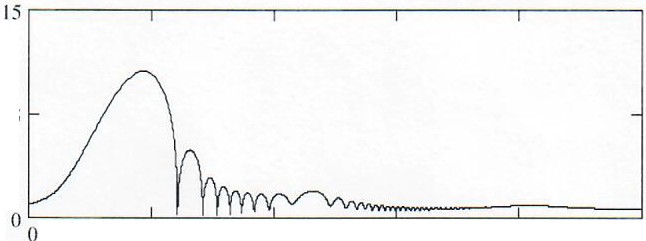
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##### Figure 1: Simulations of cavitation bubble dynamics. Set 1 - Conditions for simulations: Pump discharge pressure= 35 bar (or approx. 500 psi), R0 = 100 microns, Cavitation number= 1, Throat to pipe dia. ratio = 0.5, Estimated recovery pressure at the end of conduit = 8.5 bar.

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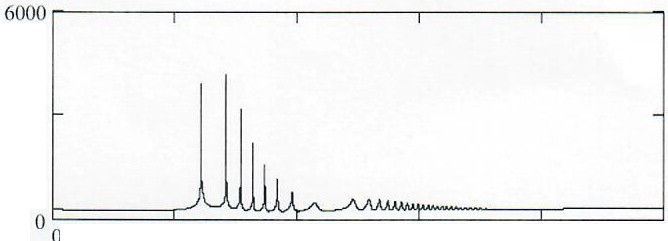
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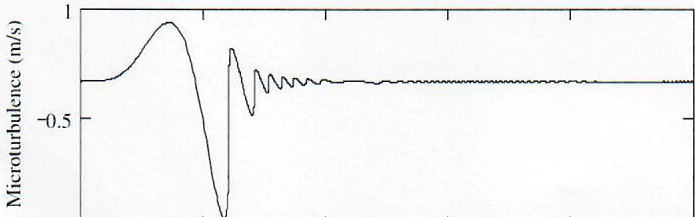
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##### Figure 2: Simulations of cavitation bubble dynamics. Set 3 - Conditions for simulations: Pump discharge pressure = 35 bar (or approx. 500 psi), Ro = 50 microns, Cavitation number= 1, Throat to pipe dia. ratio = 0.5, Estimated recovery pressure at the end of conduit= 8.5 bar.

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