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CONTENTS

Abdugaliyev A.Sh., Jalmakhanbetova R.I., Mukusheva G.K. Atomistic insight into solvent effects on the chemical structure of betulonic acid.....	11
Assembayeva E.K., Shadi D.K., Nurmukhanbetova D.E., Bozhbanov A.Zh., Gabdullina E.Zh. Effect of inulin on the quality characteristics of a fermented cheese whey-based beverage	25
Asylbekova D.D., Toktibayeva Kh.R., Kaldybayeva A.R., Zhurkhabayeva L., Tukibayeva A.S. Electrochemical behavior of phosphorous acid on a platinum electrode and its galvanostatic anodic oxidation using a lead anode	39
Auyeshov A.P., Yeskibayeva Ch.Z., Ibrayeva A.M., Alzhanov K.B., Dzholdasova E.M. Investigation of the adsorption characteristics of silica obtained from serpentinite by a combined acid–alkali method	58
Galymzhan A., Kozhabekov S., Kuanyshev A., Sansyzbay N., Abdrasilova A. Effect of octadecyl methacrylate–maleic anhydride copolymer composition on crude oil rheological properties	78
Darmenbayeva A.S., Rajasekharan R. Investigation of the structural properties of nanocellulose membranes derived from agricultural waste	95
Dmitriyeva E.A., Medvedev A., Kemelbekova A. Development of a low-temperature gas sensor based on SnO ₂ thin films and a precision measurement system for high-resistance detection	109
Dzheldybaeva I.M., Kairbekov Zh., Esenalieva M.Z., Dossumova B.T., Suimbaeva S.M. Influence of ultrasonic treatment on the structure and physicochemical properties of brown coal humic acids	125
Jumadilov T.K., Khimersen Kh., Imangazy A. Features of heavy metal ion sorption by interpolymer systems formed from homogeneous polyelectrolytes	140
Zhylykybek M., Orazbekova R.S., Yerkibaeva M.K., Aidarova A.O., Baizhumanova T.S. Co–Mg oxide catalysts for deep oxidation of methane: synthesis, structure, and catalytic activity.....	154
Imangaliyeva B., Rakhmetova G., Dossanova B., Sovet N. Technology of biological fertilizer production by hydrolysis treatment of polymer waste.....	169
Karar M.E., Beisenbayev O.K., Alibekov R.S., Shamsudin R. Starch extraction from Baidaly rice and Gala potatoes for application in biodegradable materials.....	186
Kudaibergenova G.N., Azimbayeva G.E., Kamysbayeva A.K., Izteleu B.M., Kurbanbayeva N.M. Fatty acid composition of <i>Helianthus tuberosus</i> flowers	204
Massenova A.T., Sass A.S., Torlopov I.I., Rakhmetova K.S., Malgazhdarova M.K. Tuning of surface acidity in Zn–Me-modified shaped ZSM-5–Al ₂ O ₃ alkylation catalysts.....	219
Nurislamov R.M., Nefedov A.N., Beissenbayev D.K., Leontyeva X.A., Imashev B.K. Effect of oxide films on the corrosion resistance of iron: modeling in COMSOL Multiphysics 6.2.....	238

Nurlybayev O., Kudaibergenova R., Taubayeva R., Bekaulova A., Seitmanbetova A. Textural properties of bentonite–sawdust carbon composites after metal-chloride-assisted carbonization.....	250
Puzikova D.S., Bessonova G.V., Kenzin N.R., Zhurinov M.Zh., Torlopov I.I. Modeling cavitation of oil-containing media in various hydrodynamic configurations.....	263
Rakhimov A., Zhanikulov N., Taimasov B., Potapova E., Sarsenbaev B. Calculation of the raw material composition for cement clinker with the addition of lead slag processing waste.....	285
Ryskalieva D., Baibulanova A., Yessenamanova M., Mustafina A., Samat A. Hydrogen sulfide pollution in the atmosphere of an industrial city: the potential role of evaporation fields (Atyrau, Kazakhstan)	299
Serikbayeva K.T., Chalov T.K., Sadykov K.A. Rubidium sorption from aqueous solutions by VEMEA–AGE–PEI anion exchangers.....	322
Seitkazinova A.R., Nazhipkyzy M., Yeleuov M.A., Zhaparov A.A., Kalybayeva A.K. Orange peel-derived porous activated carbon	334
Samadun A.I., Taussarova B.R., Asrakulova D.I., Nurmukhanbetova D.E. Biodegradable packaging films with copper nanoparticles: effect of NaBH ₄ concentration on morphology and antifungal properties	351
Khamitova T.O., Tyanakh S., Bolatbay A.N., Ma Fengyun, Aitbekova D.E. Linking geological genesis to the molecular and optical traits of humic acids from coal wastes.....	370
Talgatov E., Zamanbekova A., Abilmagzhanov A., Auyezkhanova A., Akhmetova S. Polymer-modified supported catalysts for the oxidation of cyclohexane with hydrogen peroxide.....	389

МАЗМҰНЫ

Абдугалимов А.Ш., Джалмаханбетова Р.И., Мукушева Г.К. Бетулон қышқылының химиялық құрылымына еріткіштер әсерін атомистикалық тұрғыдан зерттеу	11
Асембаева Э.К., Шәді Д.Қ., Нурмуханбетова Д.Е., Божбанов А.Ж., Габдуллина Е.Ж. Инулиннің ірімшік сарысуы негізіндегі ашытылған сусынның сапа көрсеткіштеріне әсері.....	25
Асылбекова Д.Д., Токтыбаева Х.Р., Қалдыбаева А.Р., Журхабаева Л., Түкібаева А.С. Фосфорлы қышқылдың платина электродындағы электрохимиялық қасиеттері және оны қорғасын анодын қолданып гальваностатикалық анодты тотықтыру.....	39
Ауешов А.П., Ескибаева Ч.З., Ибраева А.М., Алжанов К.Б., Джолдасова Э.М. Қышқылды-сілтілі комбинациялық әдіспен серпентиниттен алынған кремнеземнің адсорбциялық сипаттамаларын зерттеу	58
Ғалымжан А., Қожабеков С., Қуанышев А., Сансызбай Н., Абдрасилова А. Октадецилметакрилат пен малеин ангидридi сополимерлері құрамының мұнайдың реологиялық қасиеттеріне әсері	78
Дарменбаева А.С., Rajasekharan R. Агроқалдықтардан алынған наноцеллюлозалы мембраналардың құрылымдық қасиеттерін зерттеу.....	95
Дмитриева Е.А., Медведев А., Кемелбекова А. SnO ₂ жұқа қабықшалары негізіндегі төмен температуралы газ сенсорын және жоғары кедергілерді тіркеуге арналған прецизионды өлшеу жүйесін әзірлеу.....	109
Джелдыбаева И.М., Қайырбеков Ж., Есеналиева М.З., Досумова Б.Т., Суймбаева С.М. Ультрадыбыстық өңдеудің қоңыр көмір гумин қышқылдарының құрылымы мен физика-химиялық қасиеттеріне әсері.....	125
Джумадилов Т.К., Химэрсэн Х., Иманғазы А. Біртекті полиэлектролиттерден құрылған интерполимерлік жүйелердің ауыр металл иондарын сорбциялау ерекшеліктері.....	140
Жылқыбек М., Оразбекова Р.С., Еркибаева М.К., Айдарова А.О., Байжұманова Т.С. Метанды терең тотықтыруға арналған Co–Mg оксидті катализаторлар: синтезі, құрылымы және каталитикалық белсенділігі.....	154
Иманғалиева Б., Рахметова Г., Досанова Б., Совет Н. Полимер қалдықтарын гидролиздік өңдеу арқылы биологиялық тыңайтқыш алу технологиясы.....	169
Қарар М.Е., Бейсенбаев О.К., Алибеков Р.С., Роснах Шамсудин. Байдалы күрішпен және Гала сортты картоптан крахмал алу және оны биоыдырайтын материалдарда қолдану.....	186
Құдайбергенова Г.Н., Азимбаева Г.Е., Камысбаева А.К., Ізтелеу Б.М., Құрбанбаева Н.М. Топинамбур гүлдерінің май қышқылдық құрамы	204

Масенова А.Т., Сасс А.С., Торлопов И.И., Рахметова К.С., Малгаждарова М.К. Zn–Me-модификацияланған қалыпталған ZSM-5–Al ₂ O ₃ алкилдеу катализаторларының беттік қышқылдығын реттеу.....	219
Нурисламов Р.М., Нефедов А.Н., Бейсенбаев Д.К., Леонтьева К.А., Имашев Б.К. Темірдің коррозияға төзімділігіне оксидтік қабықшалардың әсері: COMSOL Multiphysics 6.2 бағдарламасында модельдеу.....	238
Нурлыбаев О., Кудайбергенова Р., Таубаева Р., Бекаулова А., Сейтманбетова А. Металл хлоридтері қатысында карбонизацияланған бентонит–ағаш үгіндісі көміртекті композиттерінің текстуралық қасиеттері.....	250
Пузикова Д.С., Бессонова Г.В., Кензин Н.Р., Жұрынов М.Ж., Торлопов И.И. Өртүрлі гидродинамикалық конструкциялардағы мұнай құрамды орталардың кавитация процесін модельдеу	263
Рахимов А., Жаникулов Н., Таймасов Б., Потапова Е., Сәрсенбаев Б. Қорғасын қожын өндеу қалдықтары қосылған цемент клинкерінің шикізат шихтасының құрамын есептеу	285
Серікбаева К.Т., Чалов Т.К., Садықов К.А. Сулы ерітінділерден рубидийді ВЭМЭА–АГЭ–ПЭИ аниониттерімен сорбциялау.....	299
Сейтказинова А.Р., Нажипқызы М., Елеуов М.А., Жапаров А.А., Қалыбаева А.Қ. Апельсин қабығынан алынған кеуекті белсендірілген көмір.....	322
Самадун А.И., Таусарова Б.Р., Асракулова Д.И., Нурмуханбетова Д.Е. Мыс нанобөлшектері бар биоыдырайтын қаптамалық үлдірлер: NaBH ₄ концентрациясының морфологияға және саңырауқұлаққа қарсы қасиеттеріне әсері.....	334
Хамитова Т.О., Тянах С., Болатбай А.Н., Ма Фэньюнь, Айтбекова Д.Е. Көмір қалдықтарынан бөлінген гумин қышқылдарының геологиялық генезисі мен молекулалық және оптикалық қасиеттерінің байланысы	351
Рысқалиева Д.К., Байбуланова А.А., Есенаманова М.С., Мұстафина А.Ж., Самат А.С. Өнеркәсіптік қала атмосферасының күкіртсутекпен ластануы: булану алаңдарының ықтимал рөлі (Атырау, Қазақстан)	370
Талғатов Э.Т., Заманбекова А.Т., Абильмагжанов А.З., Әуезханова А.С., Ахметова С.Н. Циклогександы сутек пероксидімен тотықтыруға арналған полимермен модификацияланған тасымалдағышқа бекітілген катализаторлар	389

СОДЕРЖАНИЕ

Абдугалимов А.Ш., Джалмаханбетова Р.И., Мукушева Г.К. Атомистическое исследование влияния растворителей на химическую структуру бетулоновой кислоты.....	11
Асембаева Э.К., Шади Д.К., Нурмуханбетова Д.Е., Божбанов А.Ж., Габдуллина Е.Ж. Влияние инулина на показатели качества ферментированного напитка на основе сырной сыворотки	25
Асылбекова Д.Д., Токтибаева Х.Р., Калдыбаева А.Р., Журхабаева Л., Тукибаева А.С. Электрохимическое поведение фосфористой кислоты на платиновом электроде и её гальваностатическое анодное окисление с использованием свинцового анода.....	39
Ауешов А.П., Ескибаева Ч.З., Ибраева А.М., Алжанов К.Б., Джолдасова Э.М. Исследование адсорбционных характеристик кремнезёма, полученного из серпентинита комбинированным кислотно-щелочным методом	58
Галымжан А., Кожабеков С., Куанышев А., Сансызбай Н., Абдрасилова А. Влияние состава сополимеров октадецилметакрилата и малеинового ангидрида на реологические свойства нефти	78
Дарменбаева А.С., Rajasekharan R. Исследование структурных свойств наноцеллюлозных мембран, полученных из агроотходов.....	95
Дмитриева Е.А., Медведев А., Кемелбекова А. Разработка низкотемпературного газового сенсора на основе тонких плёнок SnO_2 и прецизионной измерительной системы для регистрации высокоомных сопротивлений.....	109
Джелдыбаева И.М., Каирбеков Ж., Есеналиева М.З., Досумова Б.Т., Суймбаева С.М. Влияние ультразвуковой обработки на структуру и физико-химические свойства гуминовых кислот бурого угля	125
Джумадилов Т.К., Химэрсэн Х., Имангазы А. Особенности сорбции ионов тяжёлых металлов интерполимерными системами, сформированными из однородных полиэлектролитов.....	140
Жылкыбек М., Оразбекова Р.С., Еркибаева М.К., Айдарова А.О., Байжуманова Т.С. Co–Mg оксидные катализаторы для глубокого окисления метана: синтез, структура и каталитическая активность	154
Имангалиева Б., Рахметова Г., Досанова Б., Совет Н. Технология получения биологического удобрения путём гидролизной обработки полимерных отходов	169
Карар М.Е., Бейсенбаев О.К., Алибеков Р.С., Роснах Шамсудин. Получение крахмала из риса «Байдалы» и картофеля сорта «Гала» и его применение в биоразлагаемых материалах	186
Кудайбергенова Г.Н., Азимбаева Г.Е., Камысбаева А.К., Изтелеу Б.М., Курбанбаева Н.М. Жирнокислотный состав цветков топинамбура	204

Масенова А.Т., Сасс А.С., Торлопов И.И., Рахметова К.С., Малгаждарова М.К. Регулирование поверхностной кислотности Zn–Me-модифицированных формованных ZSM-5–Al ₂ O ₃ катализаторов алкилирования	219
Нурисламов Р.М., Нефедов А.Н., Бейсенбаев Д.К., Леонтьева К.А., Имашев Б.К. Влияние оксидных плёнок на коррозионную стойкость железа: моделирование в COMSOL Multiphysics 6.2	238
Нурлыбаев О., Кудайбергенова Р., Таубаева Р., Бекаулова А., Сейтманбетова А. Текстурные свойства бентонит–углеродных композитов после карбонизации в присутствии хлоридов металлов	250
Пузикова Д.С., Бессонова Г.В., Кензин Н.Р., Журинов М.Ж., Торлопов И.И. Моделирование процесса кавитации нефтесодержащих сред в различных гидродинамических конструкциях.....	263
Рахимов А., Жаникулов Н., Таймасов Б., Потапова Е., Сарсенбаев Б. Расчёт состава сырьевой шихты для цементного клинкера с добавлением отходов переработки свинцового шлака	285
Серикбаева К.Т., Чалов Т.К., Садыков К.А. Сорбция рубидия из водных растворов анионитами ВЭМЭА–АГЭ–ПЭИ.....	299
Сейтказинова А.Р., Нажипкызы М., Елеуов М.А., Жапаров А.А., Калыбаева А.К. Пористый активированный углерод, полученный из апельсиновой кожуры.....	322
Самадун А.И., Таусарова Б.Р., Асракулова Д.И., Нурмуханбетова Д.Е. Биоразлагаемые упаковочные плёнки с наночастицами меди: влияние концентрации NaBH ₄ на морфологию и антигрибковые свойства	334
Хамитова Т.О., Тянах С., Болатбай А.Н., Ма Фэньюнь, Айтбекова Д.Е. Связь геологического генезиса с молекулярными и оптическими характеристиками гуминовых кислот из угольных отходов	351
Рыскалиева Д.К., Байбуланова А.А., Есенаманова М.С., Мустафина А.Ж., Самат А.С. Загрязнение атмосферы промышленного города сероводородом: потенциальная роль полей испарения (Атырау, Казахстан)	370
Талгатов Э.Т., Заманбекова А.Т., Абильмагжанов А.З., Ауезханова А.С., Ахметова С.Н. Полимер-модифицированные нанесённые катализаторы окисления циклогексана пероксидом водорода	389

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MODELING CAVITATION OF OIL-CONTAINING MEDIA IN VARIOUS HYDRODYNAMIC CONFIGURATIONS

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Abstract. Increasing the depth of crude oil refining at domestic and foreign refineries is an important technological challenge under conditions of a growing share of heavy crude feedstock. This study presents the results of numerical modeling of hydrodynamic cavitation in various cavitation device configurations intended for the treatment of crude oil and oil-containing media. Four hydrodynamic cavitator designs were considered: a conventional Venturi nozzle, a modified Venturi nozzle with a conical flow body, a cavitator with cylindrical flow bodies, and a multichamber cavitator with sequentially arranged expansion chambers. The calculations were performed using ANSYS CFX with a two-phase “liquid oil–oil vapor” mixture model, a cavitation model based on the Rayleigh–Plesset equation, and the standard k – ε turbulence model. Pressure, velocity, and vapor-phase volume fraction distributions, as well as the spatial localization of the cavitation zone, were analyzed as comparative criteria. The results demonstrated that

the geometry of the flow section significantly affects the intensity, extent, and location of the cavitation region. The most favorable results were obtained for the cavitator with cylindrical flow bodies. At flow velocities of 0.7–0.9 m/s, a developed cavitation cloud was formed predominantly in the central part of the channel and remained separated from the walls by a liquid-phase layer. This configuration provides high cavitation activity while reducing the potential risk of cavitation erosion. Particular attention was paid to comparing cavitation intensity with the extent of cavitation contact with the device surfaces. Options for integrating cavitation devices into the process flow scheme of crude oil preparation and primary refining were proposed. Potential effects of cavitation treatment, including intensified degassing and a possible increase in the yield of light fractions, were discussed. The obtained results provide a basis for further experimental validation, optimization of cavitator geometry, and evaluation of its performance under actual process conditions.

Keywords: mathematical modeling, Rayleigh–Plesset model, ANSYS CFX, hydrodynamic cavitation, cavitation number.

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ӨРТҮРЛІ ГИДРОДИНАМИКАЛЫҚ КОНСТРУКЦИЯЛАРДАҒЫ МҰНАЙ ҚҰРАМДЫ ОРТАЛАРДЫҢ КАВИТАЦИЯ ПРОЦЕСІН МОДЕЛЬДЕУ

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Аннотация. Отандық және шетелдік мұнай өңдеу зауыттарында ауыр мұнай шикізаты үлесінің артуы жағдайында мұнайды терең өңдеу дәрежесін арттыру өзекті технологиялық мәселе болып табылады. Жұмыста мұнайды және мұнай құрамды орталарды өңдеуге арналған әртүрлі конструкциялы кавитациялық құрылғылардағы гидродинамикалық кавитацияны сандық модельдеу нәтижелері ұсынылған. Гидродинамикалық кавитаторлардың төрт нұсқасы қарастырылды: классикалық Вентури шүмегі, конустық ағынды айналып өту денесі бар модификацияланған Вентури шүмегі, цилиндрлік ағынды айналып өту денелері бар кавитатор және кеңею камералары тізбектей орналасқан көпкамералы кавитатор. Есептеулер ANSYS CFX бағдарламалық кешенінде мұнайдың сұйық және бу фазаларынан тұратын екі фазалы қоспа моделін, Рэлея–Плессет теңдеуіне негізделген кавитациялық модельді және стандартты $k-\epsilon$ турбуленттік моделін қолдану арқылы жүргізілді. Салыстыру критерийлері ретінде қысымның, жылдамдықтың және бу фазасының көлемдік үлесінің таралуы, сондай-ақ кавитациялық аймақтың кеңістікте орналасу ерекшеліктері талданды. Зерттеу нәтижелері ағын өтетін бөліктің геометриясы кавитациялық аймақтың қарқындылығына, ұзындығына және орналасуына елеулі әсер ететінін көрсетті. Ең қолайлы нәтижелер цилиндрлік ағынды айналып өту денелері бар кавитатор үшін алынды. Ағын жылдамдығы 0,7–0,9 м/с болған кезде негізінен арнаның орталық бөлігінде орналасатын және қабырғалардан сұйық фаза қабатымен бөлінетін дамыған кавитациялық бұлт қалыптасады. Мұндай конфигурация кавитациялық белсенділіктің жоғары деңгейін қамтамасыз ете отырып, кавитациялық эрозияның ықтимал қаупін төмендетуге мүмкіндік береді. Кавитация қарқындылығы мен кавитациялық аймақтың аппарат беттерімен жанасу дәрежесін салыстыруға ерекше назар аударылды. Кавитациялық құрылғыларды мұнайды дайындау және бастапқы өңдеу қондырғыларының технологиялық схемасына енгізу нұсқалары ұсынылды. Кавитациялық өңдеудің ықтимал әсерлері, соның ішінде дегазация үдерісін қарқындату және жеңіл фракциялар шығымын арттыру мүмкіндігі талқыланды. Алынған нәтижелер кавитатор геометриясын одан әрі оңтайландыруға, эксперименттік тексерулер жүргізуге және нақты технологиялық жағдайларда оның тиімділігін бағалауға негіз бола алады.

Түйін сөздер: математикалық модельдеу, Рэлея–Плессет моделі, ANSYS CFX, гидродинамикалық кавитация, кавитациялық сан

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МОДЕЛИРОВАНИЕ ПРОЦЕССА КАВИТАЦИИ НЕФТЕСОДЕРЖАЩИХ СРЕД В РАЗЛИЧНЫХ ГИДРОДИНАМИЧЕСКИХ КОНСТРУКЦИЯХ

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Аннотация. Повышение глубины переработки нефти на отечественных и зарубежных нефтеперерабатывающих заводах является актуальной задачей в условиях увеличения доли тяжелого нефтяного сырья. В работе представлены результаты численного моделирования гидродинамической кавитации в различных конструкциях кавитационных устройств, предназначенных для обработки нефти и нефтесодержащих сред. Рассмотрены четыре варианта гидродинамических кавитаторов: классическое сопло Вентури, модифицированное сопло Вентури с конусным телом обтекания, кавитатор с цилиндрическими телами обтекания и многокамерный кавитатор с последовательным расположением расширительных камер. Расчеты выполнены в программном комплексе ANSYS CFX с использованием двухфазной модели смеси «жидкость–пар нефти», кавитационной модели на основе уравнения Рэлея–Плессета и стандартной модели турбулентности $k-\varepsilon$. В качестве критериев сравнения анализировали распределение давления, скорости и объемной доли паровой фазы, а также особенности пространственной локализации кавитационной зоны. Установлено, что геометрия проточной части существенно влияет на интенсивность, протяженность и расположение кавитационной области. Наиболее благоприятные результаты получены для кавитатора с цилиндрическими телами обтекания. При скорости потока 0,7–0,9 м/с формируется развитое кавитационное облако, преимущественно локализованное

в центральной части канала и отделенное от его стенок слоем жидкой фазы. Такая конфигурация обеспечивает высокую кавитационную активность при одновременном снижении потенциального риска кавитационно-эрозионного повреждения. Особое внимание уделено сопоставлению интенсивности кавитации со степенью контакта кавитационной зоны с поверхностью аппарата. Предложены варианты интеграции кавитационных устройств в технологическую схему подготовки и первичной переработки нефти. Рассмотрены возможные эффекты кавитационной обработки, включая интенсификацию процессов дегазации и потенциальное увеличение выхода светлых фракций. Полученные результаты могут служить основой для дальнейшей экспериментальной верификации, оптимизации геометрии кавитатора и оценки эффективности его применения в реальных технологических условиях.

Ключевые слова: математическое моделирование, модель Рэлея–Плессета, ANSYS CFX, гидродинамическая кавитация, кавитационное число

Introduction. The increasing share of heavy and high-viscosity oils in the resource base of the oil industry leads to the need to develop and implement methods for intensifying feedstock preparation and processing. Heavy oils and oil sludges are characterized by increased viscosity and a high content of asphaltene-resin substances and organosulfur compounds, complicating transportation, desalting, and the production of light fractions by conventional methods (Uteev et al., 2023). Traditionally, reagent-based treatment methods are used to solve problems associated with oil viscosity and the presence of sulfur compounds. However, it is also possible to use physical, reagent-free methods of treatment of oil-containing media and oil refining products, with the initiation of chemical reactions that normally proceed only at elevated temperatures (Khamidullin et al., 2016; Peshnev et al., 2023; Askarian et al., 2017). Modern reviews on hydrodynamic cavitation consider this approach as one of the options for intensifying mass-transfer, dispersing, oxidative, and physicochemical processes, determining efficiency not only by the pressure and velocity levels, but also by the design of the cavitation unit, the bubble nucleation regime, and the stability of the cavitation zone (Zheng et al., 2022; Ranade et al., 2022; Xia et al., 2025).

Literary review. One of the promising directions for reagent-free intensification of oil preparation and refining processes is the use of hydrodynamic cavitation. Cavitation treatment of oil-containing media makes it possible to solve a number of tasks: reducing the viscosity of heavy oil, degassing the feedstock, destroying stable oil-water emulsions, changing the fractional and group composition of heavy fractions, and improving desalting and stabilization conditions. Cavitation, a process of nucleation, growth, and collapse of vapor or gas bubbles in a liquid under a local pressure decrease to values close to the saturated vapor pressure, with bubble collapse accompanied by the formation of regions with high local temperatures (5000–10000 K) and pressures (101–203 MPa), as well as intense microjets and shock waves capable of destroying asphaltene-resin associations, promoting degassing, and changing the structure of heavy fractions (Nikishin et al., 2024). For liquid petroleum products and heavy hydrocarbon

systems under cavitation treatment, studies additionally note the possibility of changing rheological characteristics, the structural state of asphaltene-resin components, phase dispersity and fractional composition (Kuimov et al., 2023; Carpenter et al., 2022).

The literature describes the application of both acoustic and hydrodynamic cavitation; however, the issues of optimizing the geometry of hydrodynamic cavitators and selecting operating modes for specific technological schemes remain relevant. Recent studies showed that cavitation treatment of oil changes its hydrocarbon composition: the content of resins and asphaltenes decreases, while the amount of oil fraction increases. According to literature data, cavitation treatment also makes it possible to remove hydrogen sulfide and sulfur from sulfur-containing compounds in oil when hydrodynamic cavitation devices are used (Peshnev et al., 2023). Modern studies emphasize the importance of the choice of cavitator design and flow regime, taking into account the target effect: dispersion, emulsification, degassing, destruction of associates, or intensification of chemical processes (Zheng et al., 2022; Xia et al., 2025; Carpenter et al., 2022; Xue et al., 2024).

Numerical modeling (CFD) of cavitation processes in real geometries of cavitation devices is of particular interest: calculations make it possible, before large-scale experiments are carried out, to obtain an understanding of the shape and position of the cavitation zone, the distribution of pressure, velocity, and vapor-phase volume fraction, and to estimate potential erosion risks and hydraulic losses (Peshnev et al., 2023). In recent computational studies, CFD approaches involving the analysis of pressure and velocity fields, vortex structures, vapor-phase volume fraction, and local cavitation number have been widely used for such tasks, allowing different designs to be compared before laboratory prototypes are manufactured (Ranade et al., 2022; Nadiri et al., 2025; Sekar et al., 2025; Poorbaba et al., 2026).

According to Bernoulli's principle, when a liquid passes through a Venturi tube, its velocity increases in the throat. At the same time, a local pressure decrease to the saturated vapor pressure occurs due to the reduction in the cross-sectional area of the throat. As a result, vapor-gas bubbles nucleate in the boundary layers of the flow; as the flow moves further downstream, these bubbles grow in size and then collapse when transported into a region of higher pressure. At the same time, for closed flow systems, the use of the cavitation number requires careful interpretation, since its calculated value depends on the selected locations for pressure and velocity evaluation, as well as on the design of the constricting element (Zheng et al., 2022; Ranade et al., 2022; Nadiri et al., 2025).

Depending on the design features of hydrodynamic cavitators, cavitation fields of different area and intensity are formed, making it possible to identify the most energy-efficient device configuration. Recent studies of Venturi reactors and rotary cavitators confirm that changes in the angles of the converging and diverging sections, the shape of the throat, the number of sequentially arranged constriction zones, and the configuration of cavitation generators significantly affect the intensity of vapor formation and the distribution of the cavitation region (Sekar et al., 2025; Poorbaba et al., 2026; Sun et al., 2021; Song et al., 2022; Xia et al., 2024).

The aim of the present study was to perform a comparative analysis of hydrodynamic

cavitation processes in an oil-containing medium for cavitation devices of different designs using numerical modeling, as well as to assess the possibility of their subsequent integration into technological schemes for crude oil preparation and primary refining.

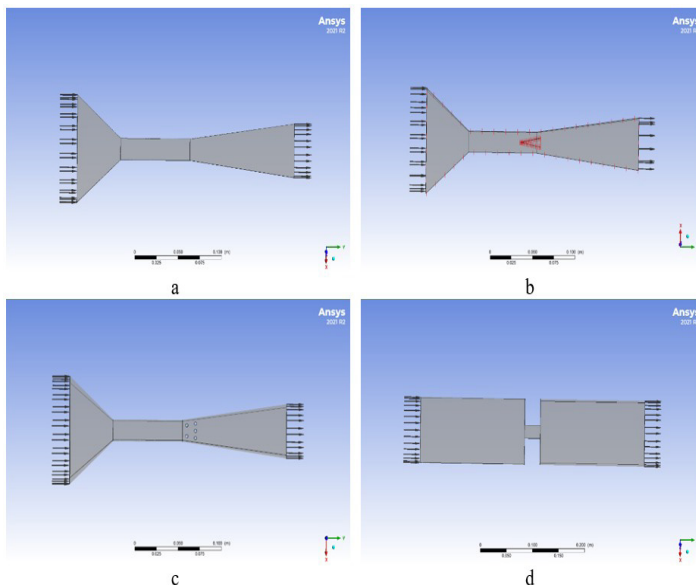
In the course of the study, three-dimensional CFD models of the flow of a two-phase “oil-oil vapor” mixture were developed with allowance for cavitation effects. The influence of the geometric parameters of the cavitator and the flow velocity on the configuration and localization of the cavitation zone was established, and the dependences of the cavitation number on the flow velocity and medium pressure were determined. The obtained data made it possible to justify the choice of the most promising cavitation device design and to propose options for its integration into the technological scheme of a primary oil refining unit. In this regard, the comparison of the designs in the present work is additionally focused not only on the occurrence of cavitation itself, but also on its spatial localization, which corresponds to the current research direction aimed at reducing erosive impact while maintaining the technological intensity of the process (Zheng et al., 2022; Ranade et al., 2022; Nadiri et al., 2025; Xia et al., 2024; Zhang et al., 2024).

2. Materials and methods

2.1. Geometric features of cavitation devices

The study considered four variants of hydrodynamic cavitators differing in the geometric parameters of the flow section and the shape of the flow bodies.

Figure 1 shows different model variants of hydrodynamic cavitation devices, each of which consists of a cylindrical body of constant or variable diameter, inside which a flow constriction zone is formed.



a – Model 1, b – Model 2, c – Model 3, d – Model 4

Figure 1 – Different models of hydrodynamic cavitation devices

The cavitation device whose model is shown in Figure 1a consists of a conventional Venturi nozzle with a smooth converging section, throat, and diffuser. The inlet diameter, D_{in} , is larger than the throat diameter, D_{th} ; the lengths of the converging section, L_c , and diffuser, L_d , were selected to ensure smooth acceleration and subsequent deceleration of the flow. This variant was used as the baseline for comparative analysis, hereinafter referred to as Model 1.

The cavitation device whose model is shown in Figure 1b consists of a modified Venturi nozzle with an axisymmetric conical flow body, with base diameter D_k and length L_k , located in the constriction zone. The cone forms a local low-pressure region in the wake zone and enhances cavitation development, hereinafter referred to as Model 2.

The cavitation device whose model is shown in Figure 1c consists of a nozzle with cylindrical flow bodies, with diameter D_c and length L_c , placed in the flow section. The cylindrical inserts form a separation zone and a developed wake flow, in which intense cavitation occurs, localized predominantly in the central part of the channel, hereinafter referred to as Model 3.

The cavitation device whose model is shown in Figure 1d consists of several expansion chambers, with diameter D_{cam} and length L_{cam} , connected by a smaller-diameter tube of diameter D_t . In each chamber, conditions are created for the nucleation and partial collapse of cavitation bubbles, which provides “stepwise” cavitation along the length of the apparatus, hereinafter referred to as Model 4.

The main dimensional characteristics, including the inlet and outlet diameters, the lengths of the converging and diffuser sections, the dimensions of the conical and cylindrical inserts, and the length of the connecting tube and chambers, were selected so as to ensure a comparable flow-section length and similar hydraulic operating conditions for all models. This made it possible to correctly perform a comparative analysis of the efficiency of different cavitation devices under identical flow regimes. This approach to comparing designs is consistent with modern studies on the optimization of cavitation reactors, in which the design parameters of the flow section are considered one of the main factors determining the nucleation region, length, and stability of the cavitation cloud (Xue et al., 2024; Nadiri et al., 2025; Sekar et al., 2025; Sun et al., 2021; Song et al., 2022; Xia et al., 2024; Zhang et al., 2024).

2.2. Physicochemical properties of the medium

The following initial assumptions were adopted in the numerical modeling: oil was considered a Newtonian incompressible liquid; the vapor phase, i.e., oil in the vapor state with the corresponding thermodynamic characteristics, was described within the model without accounting for chemical transformations; heat exchange with the walls was not considered, which is equivalent to imposing adiabatic boundary conditions; the flow at the operating flow velocities was assumed to be turbulent; and the flow temperature was assumed to be constant. The “oil-oil vapor” system was used as the working medium. The physicochemical properties of the medium are given in Table 1.

Table 1 – Physicochemical properties of oil/oil vapor

No.	Parameter	Value
Liquid phase (oil)		
1	Density ρ , kg/m ³	850
2	Dynamic viscosity μ , kg/(m·s)	$8.9 \cdot 10^{-4}$
3	Molar mass M , kg/mol	0.21
4	Thermal conductivity λ , W/(m·K)	0.6069
5	Heat capacity C_p , J/(kg·K)	2150
Oil vapor		
1	Density ρ , kg/m ³	8.59
2	Dynamic viscosity μ , kg/(m·s)	$9.86 \cdot 10^{-6}$
3	Saturated vapor pressure of oil at the calculation temperature P_{sat} , Pa	66700
4	Molar mass M , kg/mol	0.21
5	Thermal conductivity λ , W/(m·K)	0.0185

2.3. Mathematical model and numerical method

Numerical modeling was performed using the ANSYS CFX software package. For spatial discretization, an element-based finite volume approach was used with a second-order calculation scheme. The calculations were carried out in a steady-state mode until the residual convergence criterion was satisfied and the integral parameters, namely pressure drop and average vapor-phase volume fraction in the control sections, were stabilized. The motion of the two-phase “liquid-oil vapor” system was described by a system of Reynolds-averaged Navier–Stokes equations for an incompressible liquid, taking into account turbulence and the cavitation process. The standard k – ϵ turbulence model was used to close the turbulent stresses. The type of multiphase model was homogeneous mixture.

Cavitation processes were modeled within an approach based on the Rayleigh–Plesset equation, which describes the dynamics of a single spherical bubble in a variable pressure field (1):

$$R \frac{d^2 R}{dt^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 = \frac{1}{\rho} \left(p_{\infty} - p_v - \frac{2\sigma}{R} - \frac{4\mu}{R} \frac{dR}{dt} \right), \quad (1)$$

where R is the bubble radius, t is time, dR/dt is the rate of change of the bubble radius, $d^2 R/dt^2$ is the acceleration of the change in bubble radius, ρ (or ρ_l) is the liquid-phase density, p_{∞} is the pressure in the surrounding liquid far from the bubble, p_v is the pressure inside the bubble / vapor pressure in the bubble, σ is the surface tension coefficient, and μ is the dynamic viscosity of the liquid.

The development of the vapor-phase volume fraction was determined from a transport equation with source terms depending on the local pressure and liquid properties (2):

$$\alpha_v = 1 - \alpha_l = \frac{\frac{4}{3} \pi R_B^3 n_0}{1 + \frac{4}{3} \pi R_B^3 n_0}, \quad (2)$$

where α_v is the vapor-phase volume fraction, α_l is the liquid volume fraction, R_b is the bubble radius or characteristic cavitation nucleus radius, n_0 is the concentration of cavitation nuclei / number of bubbles per unit volume.

The structural and geometric parameters of the considered cavitator models were represented as a three-dimensional computational mesh with local element refinement in the channel constriction region and in the zone of expected cavitation development. To describe the flow near solid walls more correctly, prismatic layers were formed in the near-wall region, making it possible to account for the features of the boundary layer. The total number of control volumes for each computational model was set within a comparable range, ensuring the correctness of the subsequent comparison of the modeling results. These assumptions are typical for the initial stage of CFD comparison of cavitators; however, when moving to pilot-scale verification, they require refinement by accounting for the rheological nonlinearity of heavy oil systems, bubble polydispersity, and possible unsteadiness of the cavitation cloud (Ranade et al., 2022; Kuimov et al., 2023; Poorbaba et al., 2026).

Additionally, a mesh convergence check was performed. When the number of computational elements was increased, the change in the main monitored parameters did not exceed the acceptable level, which made it possible to consider the selected mesh discretization sufficient for obtaining stable and comparable computational results.

The following set of boundary conditions was used in the calculations:

At the inlet of the cavitator nozzle, a prescribed flow velocity averaged over the cross-section was specified. Five velocity values were considered: 0.5, 0.6, 0.7, 0.8, and 0.9 m/s.

At the outlet of the cavitator nozzle, a prescribed static pressure was specified, corresponding to the operating pressure range in the pipeline of the oil preparation unit.

At the cavitator walls, the no-slip condition was applied, and heat flux through the walls was absent, corresponding to adiabatic walls.

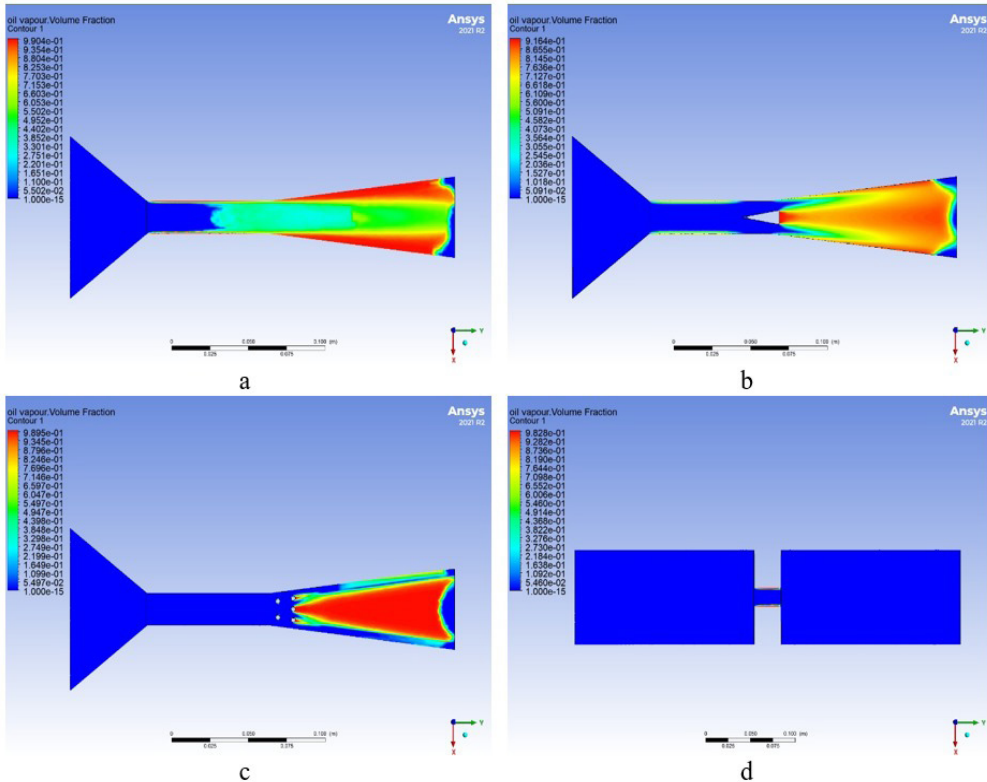
In each calculation series, the fields of vapor-phase volume fraction, velocity, and pressure were recorded, and the local cavitation number was also calculated and used to compare cavitation activity in cavitation devices of different configurations. The model did not account for chemical transformations, flow unsteadiness, bubble polydispersity, or heat exchange with the walls.

3. Results

Effect of cavitator design features on the flow structure

According to the numerical modeling results, the shape of the flow section and flow bodies of the cavitation device has a key influence on the flow structure and the distribution of the cavitation zone. The distribution of the vapor-phase volume fraction α_v was used as the main criterion for the presence and development of cavitation in the channel. Regions where $\alpha_v > \alpha_{crit}$, for example, 0.05–0.1, were considered active cavitation zones.

Figure 2 shows typical distributions of the vapor-phase volume fraction in cavitators of different configurations at the studied flow velocities.



a – Model 1, b – Model 2, c – Model 3, d – Model 4

Figure 2 – Simulation results for the distribution of the vapor-phase volume fraction in cavitators of different configurations (flow velocity 0.8 m/s)

For the basic cavitator model shown in Figure 2a, a conventional Venturi nozzle, the low-pressure zone is formed in the throat region and in the initial part of the diffuser. When the local pressure reaches values close to the saturated vapor pressure of the oil-containing medium, the cavitation process is initiated in this zone. The cavitation cloud comes into partial contact with the throat walls and gradually collapses as the flow moves downstream. The configuration of the conventional Venturi nozzle provides noticeable cavitation activity; however, it is accompanied by an increased load on the wall material in the throat region, which potentially increases the risk of cavitation erosion.

In the cavitator shown in Figure 2b, the modified Venturi nozzle is supplemented with an axisymmetric conical flow body installed in the constriction zone. As a result, the region of minimum pressure shifts to the wake zone behind the cone. Cavitation bubbles nucleate in the zone of flow separation and intense shear stresses. The cavitation cloud is more elongated along the channel axis; however, in a number of regimes it remains partially associated with the cone surface and the diffuser wall, which may also be critical from the standpoint of erosion resistance.

The most pronounced advantages in terms of spatial localization of the cavitation zone and reduction of the risk of cavitation erosion are observed for the cavitator with cylindrical flow bodies shown in Figure 2c. The modeling results show that, in this design, the cavitation zone is formed predominantly in the central part of the channel, in the wake region behind the cylindrical inserts, and is separated from the walls by a distinct layer of the liquid phase. Such a spatial configuration reduces the probability of direct impact of cavitation microjets and shock waves on the channel walls while maintaining a high vapor-phase fraction in the flow volume. Therefore, this design makes it possible to combine intense cavitation development in the working volume with a reduced probability of cavitation erosion of the cavitator walls.

In the multichamber cavitator shown in Figure 2d, cavitation zones are formed mainly in the smaller-diameter connecting tube, as well as in the inlet and outlet regions of the chambers. As the flow passes through the sequentially arranged chambers, alternating regions of nucleation, growth, and collapse of cavitation bubbles are observed. Such a stepwise nature of cavitation action may potentially promote more intense disaggregation of stable asphaltene-resin structures. At the same time, this design requires additional analysis in terms of the uniformity of treatment of the oil-containing medium, the stability of the cavitation regime, and the magnitude of hydraulic losses.

4. Discussion

4.1. Effect of flow velocity on cavitation development

In recent literature, additional criteria related to the vapor volume fraction, cavitation cloud localization, vortex structures, and the area of potential erosive contact have been used for similar tasks, increasing the analysis informativeness compared with the use of the cavitation number alone (Nadiri et al., 2025; Poorbaba et al., 2026; Xia et al., 2024; Zhang et al., 2024).

To compare flow regimes and assess the degree of development of cavitation phenomena in the considered designs of hydrodynamic cavitators, a combined approach was used in the present work, based both on the analysis of the dimensionless cavitation number σ and on the interpretation of the distributions of the vapor-phase volume fraction α_v obtained as a result of numerical modeling. The classical cavitation number σ is determined through local flow parameters, namely pressure, density, and velocity, and characterizes the thermodynamic tendency of the system to cavitation onset (Omelyanyuk et al., 2022). However, in numerical modeling of complex flows in cavitator designs with design-scale dimensions, not only the numerical value of the cavitation number σ is informative, but also its physical manifestation through the spatial distribution of the vapor phase. In this regard, the present work also focuses on regions in which α_v exceeds a certain threshold, $\alpha_v > 0.05\text{--}0.1$, which are considered zones of developed cavitation. At the same time, an increase in the area and intensity of these zones, as well as their displacement toward the central part of the flow, are interpreted as signs of a decrease in local cavitation number values and a transition of the system to a stable developed cavitation regime. Thus, visualization of the α_v fields actually serves as a tool for spatially resolved assessment of the cavitation regime and makes it possible to compare different designs not only by the fact of cavitation occurrence, but also by the nature of its distribution within the flow volume.

Figure 3 presents the numerical modeling results for the distribution of the vapor-phase volume fraction α_v for four different configurations of hydrodynamic cavitators, Models 1–4, at flow velocities of 0.5, 0.6, 0.7, 0.8, and 0.9 m/s. For each velocity, the α_v fields are shown, allowing to trace the evolution of the cavitation zone as the hydrodynamic load increases.

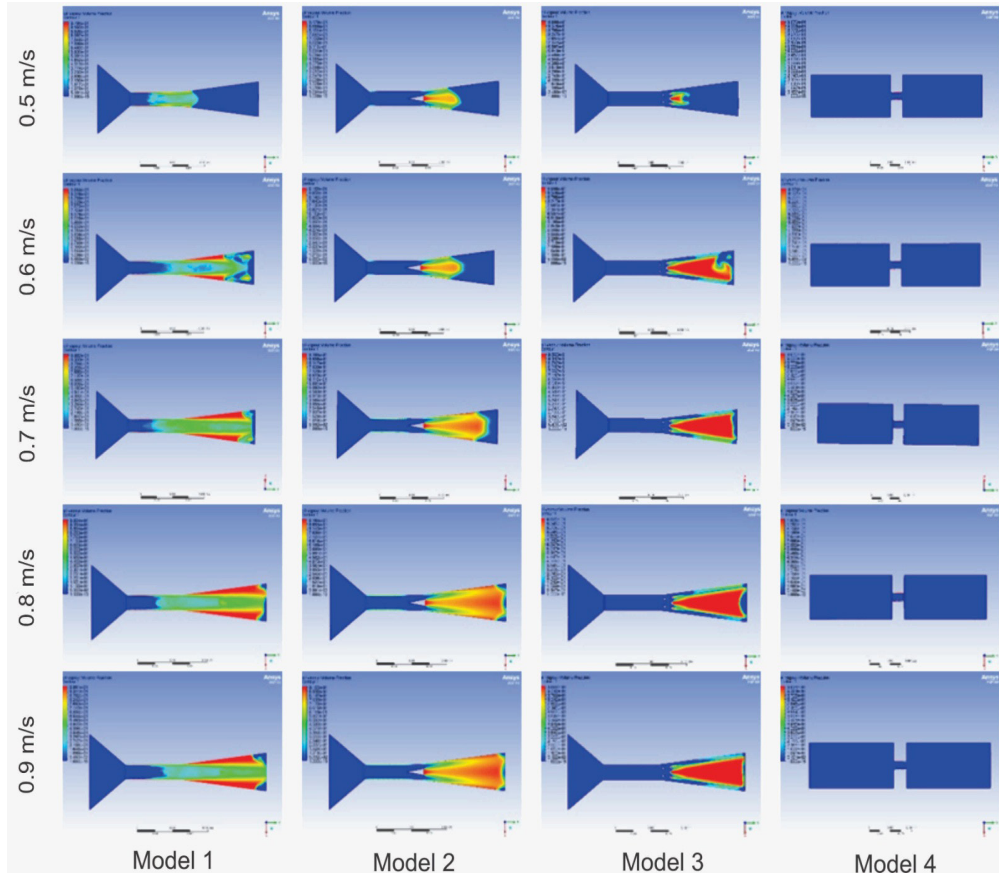


Figure 3 – Simulation results for the distribution of the vapor-phase volume fraction in cavitators of different configurations at flow velocities of 0.5, 0.6, 0.7, 0.8, and 0.9 m/s

Analysis of the obtained results shows that, at the minimum studied flow velocity of 0.5 m/s, cavitation effects are weakly expressed in all considered configurations. For the conventional Venturi nozzle, Model 1, only local initiation of the cavitation process is observed in the throat region; in this case, the vapor-phase volume fraction is low, and the cavitation cloud has limited dimensions. In the modified design with a conical flow body, Model 2, the cavitation cloud forms in the wake zone behind the cone; however, its intensity also remains low. In the cavitator with cylindrical inserts, Model 3, more pronounced localization of the cavitation cloud in the central part of the flow is observed

at this velocity, although the overall degree of its development remains limited. For the multichamber cavitator, Model 4, the cavitation process is practically absent, indicating insufficient intensity of hydrodynamic impact in this configuration.

When the velocity is increased to 0.6 m/s, a noticeable intensification of cavitation phenomena occurs in all models. In Model 1, the cavitation zone expands substantially and extends into the diffuser section, with a significant part of it coming into contact with the channel walls. In Model 2, an increase in the length of the cavitation cloud in the wake region behind the cone is observed. The most substantial changes are recorded for Model 3, where a developed cavitation zone is formed, localized predominantly in the central part of the flow, which indicates a favorable pressure and velocity distribution. In Model 4, cavitation remains weakly expressed and localized in separate sections of the transition zones.

At velocities of 0.7–0.9 m/s, a transition to a developed cavitation regime occurs. Model 1 is characterized by the formation of an extended cavitation cloud; however, it is largely associated with the channel walls, which may lead to increased erosive impact. In Model 2, the cavitation zone becomes more stable and elongated along the flow axis; however, partial contact with the walls and the surface of the flow body is preserved. The most favorable pattern is observed for Model 3: the cavitation cloud has considerable length and high intensity, while it is clearly localized in the central part of the channel and separated from the walls by a layer of liquid phase. This indicates the formation of a regime in which high cavitation activity is achieved while reducing the risk of cavitation erosion. In Model 4, even at the maximum velocities, cavitation remains local and stepwise in nature, being distributed among individual chambers and transition sections, which leads to a less uniform effect on the flow.

Thus, analysis of the results presented in Figure 3 makes it possible to draw conclusions about the influence of flow velocity and cavitation device design on the formation and localization of the cavitation zone. An increase in velocity leads to a decrease in the local cavitation number and an increase in the vapor-phase volume fraction; however, the nature of cavitation distribution is determined by the design of the flow section. From the standpoint of forming a technologically preferable regime, namely developed cavitation in the flow volume with minimal contact with the walls, the best results were recorded for Model 3 with cylindrical flow bodies, especially in the velocity range of 0.7–0.9 m/s, confirming the feasibility of its further use and optimization.

For a quantitative comparison of the cavitator models, the classical cavitation number alone is not sufficient, since this parameter characterizes the general tendency of the flow to develop cavitation but does not fully reflect the spatial localization of the cavitation zone, the degree of its contact with the walls, or the distribution of the vapor phase over the channel cross-section. In this regard, in the present work, along with the local cavitation number, additional integral criteria calculated from the vapor-phase volume fraction fields are proposed.

The classical cavitation number σ was determined using (3):

$$\sigma = \frac{P - P_{\text{sat}}}{0.5\rho V^2}, \quad (3)$$

where P is the absolute flow pressure, P_{sat} is the saturated vapor pressure of the liquid at the calculation temperature, ρ is the liquid-phase density, and V is the characteristic flow velocity.

From a physical standpoint, a decrease in the cavitation number corresponds to an increase in the probability and intensity of cavitation development, whereas an increase in the cavitation number indicates weakening of the cavitation regime (Omelyanyuk et al., 2022). Therefore, all other conditions being equal, the geometry that ensures lower values of σ in the working zone is more effective in terms of cavitation excitation.

However, for the treatment of oil-containing media, not only the intensity of the cavitation process but also the nature of its spatial distribution is of fundamental importance. Taking this into account, the following additional dimensionless indicators were introduced (Zhang et al., 2022).

The integral degree of cavitation K_V over a cross-section or volume was defined as follows (4):

$$K_V = \frac{1}{V} \int_V \alpha_v(V) dV, \quad (4)$$

where α_v is the local vapor-phase volume fraction.

The parameter K_V makes it possible to estimate the total intensity of vapor formation in the flow section.

To assess the position of the cavitation zone relative to the flow axis, the centrality index K_C was introduced (5):

$$K_C = 1 - \frac{\int_A \alpha_v \frac{|r|}{R} dA}{\int_A \alpha_v dA}, \quad (5)$$

where r is the distance from the considered point to the channel axis, and R is the local flow radius. The closer K_C is to unity, the more strongly the cavitation zone is concentrated in the central part of the flow. A decrease in K_C indicates displacement of cavitation toward the walls.

This approach is consistent with modern CFD studies, in which the vapor-phase volume fraction is considered one of the key computational indicators of the intensity of the cavitation regime and the spatial position of the cavitation region (Sekar et al., 2025; Poorbaba et al., 2026; Xia et al., 2024; Zhang et al., 2024).

To assess the risk of cavitation impact on the housing material, the near-wall contact index K_w was additionally proposed (6):

$$K_w = \frac{\int_{A_w} \alpha_v dA}{\int_A \alpha_v dA}, \quad (6)$$

where A_w is the region adjacent to the channel wall within a specified near-wall layer.

An increase in K_w indicates an increase in the fraction of the cavitation zone located in the immediate vicinity of the wall and, consequently, a potential increase in erosion hazard.

Taking into account the technological objective, which consists in forming intense cavitation predominantly in the flow volume rather than near the apparatus walls, the overall indicator K_{eff} can be used as a generalized efficiency criterion. This indicator increases with increasing total cavitation intensity and its displacement toward the axial part of the flow, but decreases with increasing near-wall contact of the cavitation cloud (7):

$$K_{\text{eff}} = K_v \cdot K_c \cdot (1 - K_w). \quad (7)$$

Analysis of the obtained pressure, velocity, and vapor-phase volume fraction fields showed that, with increasing flow velocity, the cavitation number decreases for all considered cavitator variants, while the volume of the active cavitation zone increases. At the same time, comparison based only on the value of the cavitation number σ does not allow the variants to be correctly ranked in terms of their practical applicability, since equally low values of σ may correspond both to desirable volume cavitation and to undesirable near-wall cavitation. For this reason, the combined use of the criteria σ , K_v , K_c , and K_w is the most appropriate. Therefore, the introduction of additional integral indicators makes it possible to more correctly assess not only the overall cavitation activity, but also its technological suitability in terms of the service life of the apparatus and the directionality of its effect on the treated medium (Zheng et al., 2022; Ranade et al., 2022; Carpenter et al., 2022; Nadiri et al., 2025).

In Table 2, the values of K_v , K_c , K_w , and K_{eff} are presented as normalized comparative indices obtained based on the analysis of the vapor-phase volume fraction α_v distributions in the computational domain. The presented values are semi-quantitative and are intended for intergeometry comparison of cavitators at identical flow velocities.

Model 1 is characterized by the formation of developed cavitation in the throat and in the initial part of the diffuser; however, a significant part of the cavitation cloud is associated with the channel wall. This leads to acceptable values of K_v , but is simultaneously accompanied by comparatively increased values of K_w , which limits the service reliability of the design.

In Model 2 with a conical flow body, displacement of the cavitation zone into the wake region behind the body is observed; however, in a number of regimes, partial contact is retained both with the surface of the flow body and with the channel wall. In this regard, this model occupies an intermediate position between the baseline variant and the more favorable configuration with cylindrical inserts.

The most preferable results according to the set of criteria were obtained for Model 3 with cylindrical flow bodies. This geometry is characterized by comparatively low values of the cavitation number in the operating velocity range, high values of K_V , as well as an increased centrality index K_C with a reduced near-wall contact index K_W . This means that the cavitation cloud is formed predominantly in the central part of the flow and has a lesser effect on the apparatus walls.

Table 2 – Results of cavitation activity assessment for different cavitator configurations

Model	Velocity, m/s	Integral degree of cavitation, K_V	Centrality index, K_C	Near-wall contact index, K_W	Overall efficiency indicator, K_{eff}
Model 1	0.5	0.40	0.41	0.20	0.57
Model 2		0.26	0.52	0.14	0.95
Model 3		0.11	0.61	0.00	1.00
Model 4		0.01	0.11	0.50	0.00
Model 1	0.6	0.99	0.39	0.16	0.43
Model 2		0.35	0.52	0.13	0.40
Model 3		0.59	0.57	0.10	1.00
Model 4		0.01	0.11	0.63	0.00
Model 1	0.7	0.95	0.45	0.16	0.72
Model 2		0.59	0.50	0.14	0.67
Model 3		0.64	0.54	0.11	1.00
Model 4		0.01	0.13	0.59	0.00
Model 1	0.8	1.00	0.41	0.17	0.57
Model 2		0.67	0.49	0.15	0.71
Model 3		0.62	0.54	0.11	1.00
Model 4		0.01	0.11	0.51	0.00
Model 1	0.9	0.98	0.40	0.16	0.45
Model 2		0.68	0.48	0.16	0.55
Model 3		0.65	0.56	0.10	1.00
Model 4		0.01	0.13	0.60	0.00

Model 4 provides stepwise development of cavitation along the length of the apparatus; however, the distribution of cavitation activity between individual sections of the flow path is less uniform. At the same time, this model requires additional assessment of hydraulic losses and regime stability, which makes its unambiguous ranking difficult without extended analysis.

Thus, quantitative assessment of cavitation activity should be based not only on the cavitation number, but also on integral characteristics of the vapor-phase distribution. This approach makes it possible to compare cavitators of different configurations more correctly and to identify designs that provide not simply intense cavitation, but technologically preferable cavitation: volumetric, stable, and minimally associated with the channel walls.

Comparison of the numerical modeling results based on the pressure, velocity, and vapor-phase volume fraction fields, as well as on the system of quantitative criteria

σ , K_V , K_C , K_W , and K_{eff} showed that the most favorable combination of cavitation intensity and reduced risk of erosion damage is provided by Model 3 with cylindrical flow bodies. In this configuration, the cavitation zone is formed predominantly in the wake region behind the cylindrical inserts and is localized in the central part of the channel, maintaining a liquid layer between the region of developed vapor phase and the apparatus walls. This distribution provides high cavitation activity in the working flow volume while limiting the direct impact of microjets, shock waves, and local pressure pulses on the housing material.

Model 1, represented by a conventional Venturi nozzle, provides a pronounced pressure drop in the throat region and the formation of developed cavitation; however, the cavitation cloud is largely associated with the channel walls. This increases the probability of local cavitation erosion and limits the feasibility of long-term operation of this design when treating high-viscosity and potentially corrosive oil-containing media. Model 2 with a conical flow body is characterized by a more favorable flow structure compared with the baseline variant, since the region of intense cavitation is shifted into the wake zone behind the flow body; at the same time, in a number of regimes, partial interaction of the cavitation cloud with solid surfaces is preserved, as a result of which the reduction in erosive load remains incomplete. Model 4 is of interest as a variant of stepwise cavitation action, in which the stages of bubble nucleation, growth, and collapse are sequentially realized in different sections of the apparatus. Such a regime may be promising for the disaggregation of asphaltene-resin structures and oil degassing; however, the increased complexity of the flow section, a possible increase in hydraulic resistance, and the nonuniform distribution of cavitation activity along the apparatus length require further optimization.

Thus, for the stated task, associated with the formation of developed cavitation predominantly in the flow volume while minimizing near-wall impact, the most rational configuration is Model 3. This variant is characterized by a combination of a reduced cavitation number in the working zone, a high integral degree of cavitation, pronounced central localization of the cavitation cloud, and a lower risk of erosive impact on the walls. The optimal velocity range for this configuration is 0.7–0.9 m/s; within this range, a stable regime of volumetric cavitation is ensured without substantial expansion of the near-wall contact zone. Therefore, Model 3 can be recommended as the baseline geometry for further experimental verification, design refinement, and subsequent integration into technological schemes for crude oil preparation and primary refining. The obtained results require verification on a laboratory test bench, followed by comparison of the calculated and experimental data.

4.2. Integration options for a hydrodynamic cavitator in a crude oil preparation and primary refining unit

The modeled designs of cavitation devices are intended for implementation in existing crude oil preparation and primary refining units with minimal modification of the current process scheme. Model 3, in the velocity range of 0.7–0.9 m/s, is the most preferable for industrial application due to localization of the cavitation zone within the flow volume and achievement of a developed cavitation regime at moderate cavitation

numbers. At least two principal options are possible for incorporating a hydrodynamic cavitator into the technological flow.

Figure 4 shows a scheme for incorporating a hydrodynamic cavitation device into the technological scheme of primary oil refining, with installation options at two points proposed: before and after the electrostatic dehydrators.

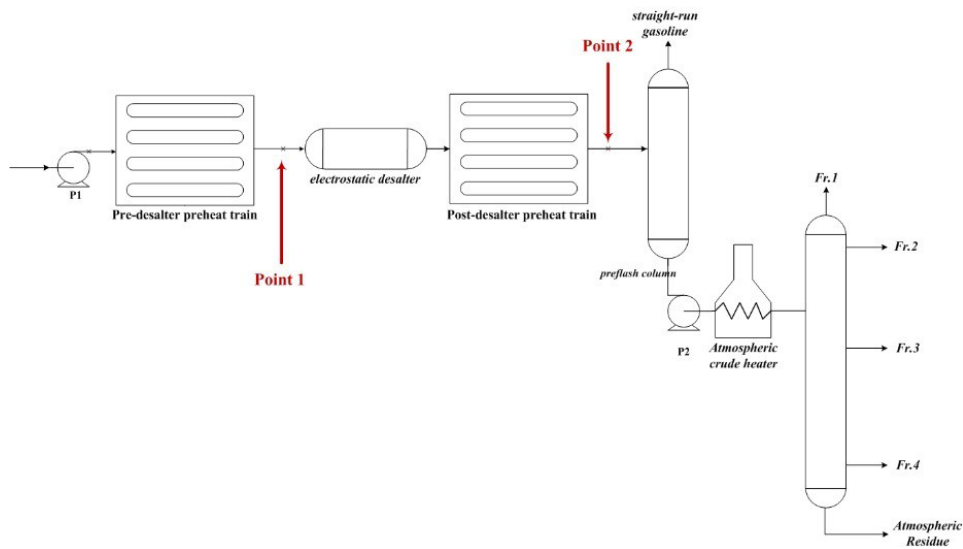


Figure 4 – Proposed placement of a hydrodynamic cavitation device in the primary oil refining process flow diagram

In the first variant (Point 1), the cavitator is installed in the feedstock line after the heaters, but before the electrical desalting and dehydration unit. Under these conditions, preheated oil with increased viscosity and containing mechanical impurities, salts, and dissolved gases enters the cavitator. The expected effects of implementing cavitation treatment at the oil preparation stage include intensification of degassing due to the release of dissolved and finely dispersed gases under the action of cavitation phenomena; increased desalting efficiency due to the destruction and dispersion of stable oil–water emulsions; fragmentation of large droplets and impurity agglomerates with improved conditions for coalescence of the aqueous phase; and homogenization of the rheological and physicochemical properties of oil in the flow due to mixing and partial disaggregation of asphaltene-resin associations. At the same time, the disadvantages of installing the cavitation device at Point 1 include the need to arrange a system for removal and utilization of the released gases, since under intense cavitation action part of the light hydrocarbon components and sulfur-containing compounds may pass into the gas phase already at the preparation stage, which requires ensuring their safe discharge or return to the appropriate technological streams.

In the second variant (Point 2), the cavitator is incorporated into the feedstock supply line directly before the gasoline-stripping (stabilization) column. In this case,

the gas released during cavitation treatment is almost immediately directed to the column, where conditions are provided for its separation and subsequent utilization. The advantages of placing the cavitator directly before the column include elimination of the need for a separate degassing unit, since the gas released under cavitation action is directed immediately into the column apparatus; combining cavitation treatment with stabilization and gasoline-stripping processes, which may potentially provide more complete recovery of light fractions and an increase in the depth of separation; and the possibility of integrating the cavitator into the existing technological scheme with a minimal amount of changes to the piping arrangement. At the same time, with this arrangement, the probable increase in the corrosive aggressiveness of the medium in the upper part of the column and adjacent communications should be taken into account due to an increase in the content of H_2S and other sulfur-containing components in the gas phase, which necessitates a justified selection of equipment materials and the application of adequate corrosion-protection measures.

In addition to crude oil treatment, hydrodynamic cavitators can be used to intensify processes associated with heavy petroleum products, including fuel oil, tar, bitumen, and oil sludges. Possible areas of application of hydrodynamic cavitation include reducing the viscosity of fuel oil and tar in order to facilitate their transportation, pumping, and combustion through degassing and partial destruction of asphaltene-resin structures; treatment of bitumen and road binders for targeted modification of their structural-mechanical and rheological characteristics; processing of oil sludges, including dispersion of the solid phase, removal of the gas component, and partial destruction of high-molecular compounds, which may simplify subsequent separation and utilization; and preparation of composite fuels, including mixtures of fuel oil, heavy petroleum fractions, and coal–water suspensions, in which cavitation action may be used to intensify mixing, increase system homogeneity, and improve stability during storage and transportation.

For these areas, additional studies are required, including adaptation of cavitation device designs to more viscous media, experimental verification of treatment efficiency, and assessment of the effect on combustion parameters, emissions, and equipment durability. In addition, for transition to industrial application, it is necessary to take into account apparatus scale-up, stability of the cavitation regime under changes in flow rate, hydraulic losses, and the possible influence of cavitation on subsequent separation stages and the corrosion state of the equipment (Song et al., 2022).

5. Conclusion

A numerical study of hydrodynamic cavitation processes in an oil-containing medium was carried out for four designs of cavitation devices. It was established that the design of the flow section determines the intensity, shape, and localization of the cavitation zone. As the flow velocity increases, the cavitation number decreases, and a transition occurs from initial vapor formation regimes to stable developed cavitation.

The use of the cavitation number alone is insufficient for a correct comparison of cavitators, since this parameter does not reflect the distribution of the vapor phase in the flow volume or the degree of its contact with the apparatus walls. Therefore,

a multicriteria approach was applied, including assessment of the integral degree of cavitation, the centrality of the cavitation cloud, and near-wall contact.

The most preferable results were obtained for the design with cylindrical flow bodies. In this variant, the cavitation zone is formed predominantly in the central part of the flow while a liquid layer is preserved near the channel walls, which provides a combination of high cavitation activity and a reduced risk of erosion damage to the equipment. The rational velocity range for this design is 0.7–0.9 m/s.

The obtained results confirm the prospects of using hydrodynamic cavitation as a reagent-free method for intensifying crude oil preparation and primary refining processes, including degassing, viscosity reduction, destruction of emulsion structures, and treatment of heavy fractions. Further studies should focus on experimental verification, assessment of hydraulic losses, consideration of the properties of real oil systems, and techno-economic justification for the implementation of cavitation devices. The next stage should involve comparison of the calculated data with experimental results on changes in viscosity, gas content, fractional composition, and stability of emulsion systems, since these indicators are used in modern studies of cavitation treatment of petroleum and heavy hydrocarbon media.

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